Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CALCULATION PACKAGE COVER SHEET

Client: Gowanus Canal Remedial Design Group (RD Group) **Project:** Gowanus Canal Superfund Site **Project #:** HPH106A

TITLE OF PACKAGE: **TREATMENT LAYER DESIGN EVALUATION**

PREPARATION	**CALCULATION PREPARED BY:** (Calculation Preparer, CP)	Signature	*[signature]*	18 May 2017
		Name Dogus Meric, Ph.D.		Date
REVIEW	**ASSUMPTIONS & PROCEDURES CHECKED BY:** (Assumptions & Procedures Checker, APC)	Signature	*[signature]*	19 May 2017
		Name Jennifer Wilkie, Ph.D., P.E.		Date
	COMPUTATIONS CHECKED BY: (Computation Checker, CC)	Signature	*[signature]*	19 May 2017
		Name Jennifer Wilkie, Ph.D., P.E.		Date
BACK-CHECK	**BACK-CHECKED BY:** (Calculation Preparer, CP)	Signature	*[signature]*	19 May 2017
		Name Dogus Meric, Ph.D.		Date
APPROVAL	**APPROVED BY:** (Calculation Approver, CA)	Signature	*[signature]*	19 May 2017
		Name J.F. Beech, Ph.D., P.E.		Date

REVISION HISTORY:

NO.	DESCRIPTION	DATE	CP	APC	CC	CA
0	TB4 Pilot Study Design – Issued for Bid	5/19/2017	DM	JAW	JAW	JFB

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **1**   of   **101**

CP: **DM** Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

TREATMENT LAYER DESIGN EVALUATION

INTRODUCTION AND PURPOSE

As outlined in the September 2013 Record of Decision (ROD) (EPA, 2013), a multilayered capping system ("cap") will be constructed within the Canal to: (i) provide a layer at the bottom of the Canal that is physically stable and meets remedy performance criteria for contaminants of concern (COCs); and (ii) prevent unacceptable amounts of contaminants, including dissolved-phase constituents and non-aqueous phase liquid (NAPL), from migrating into the overlying Canal surface water at levels that can pose risk to ecological receptors.

The cap will consist of three primary layers (illustrated in Drawing Sheet C-2): (i) a treatment layer, (ii) an isolation and filter layer, and (iii) an armor layer. The isolation and filter layer along with sand integrated into the armor layer will also serve as an ecological habitat layer. A sand based leveling layer is also planned for the base of the cap to provide a separation between the sediment and cap treatment layer and as a means of creating a more uniform surface elevation following dredging. The calculation package presented herein addresses the design of the treatment layer in the 4th St. Turning Basin (TB4) Pilot Study Area. The design of the ecological habitat layer and the armoring layer are addressed separately.

The treatment layer will consist of a mixture of reactive amendments (e.g., oleophilic clay and granular activated carbon [GAC]) and sand. The treatment layer is designed to achieve the following remedial action objective (RAOs) in the TB4 Pilot Study Area: "isolate and prevent the migration of polycyclic aromatic hydrocarbons (PAHs) and residual non-aqueous phase liquid (NAPL) from native sediments" (EPA, 2013).

This calculation package focuses on oleophilic clay treatment layer calculations for NAPL sequestration and model simulation for the GAC-based treatment layer to treat dissolved-phase contaminants. Although the oleophilic clay layer will also adsorb dissolved-phase organics (Reible, 2005; Meric et al., 2014), the treatment layer design model simulations rely solely on the GAC layer for the dissolved-phase.

The treatment layer thickness and composition required to isolate potentially mobile NAPL and prevent dissolved PAH breakthrough above specific performance criteria over a 100-year cap design life were calculated. Laboratory testing of carbon-based amendments was conducted during Phase 1 of the PD-17: Treatability Testing of Active Cap Layer Materials (PD-17) pre-design investigation to evaluate sorption performance of various amendment alternatives are viable for the Site.

Geosyntec▷

consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

DESIGN METHODOLOGY AND PARAMETERS

The design methodology, assumptions, and parameters for the treatment layer are described for the oleophilic clay and GAC layers in the following sections, respectively.

Oleophilic Clay Layer

The oleophilic clay (e.g., Organoclay®) layer composition and thickness is based on the findings from the PD-17 bench-scale treatability study to assess the NAPL sorption capacity of various oleophilic clay products (Geosyntec, 2016a), and vendor specified physical parameters (e.g., dry density; reduction in hydraulic conductivity). The input parameters, assumptions, calculations, and performance criteria are summarized in detail in subsequent sections.

Input Parameters and Assumptions

The input values used in the calculation include physical and chemical properties of the oleophilic clay treatment layer. The physical and chemical input parameters used in the calculation are summarized in Table 1.

Chemical parameters (e.g., NAPL sorption capacity) of oleophilic clays were measured during the PD-17 laboratory testing (Geosyntec, 2016a). The NAPL sorption capacity of various oleophilic clays are provided as mass of free-product NAPL sequestered by a mass of oleophilic clay. As summarized in Table 1, the highest NAPL sorption capacities were exhibited by Organoclay® PM-200 (180% ± 9%) and PM-199 (166% ± 6%), which is consistent with the range of NAPL sorption capacities reported by the manufacturer (CETCO, 2017; e.g., 172% to 330% DNAPL sorption capacity for PM-200). While Activated Clay ET-1 (74%), oil sorption media OMC-P (72%), and AquaGate + Organoclay (63%) exhibited only slightly better NAPL sorption capacity relative to sand-only controls (45%). The free-product NAPL sorption by silica sand is thought to be the result of physical isolation rather than chemical sorption. Because ET-1, OMC-P, and AquaGate + Organoclay did not provide notable chemical sorption compared to controls, they were not included in the oleophilic clay layer calculations.

The oleophilic clays retained for design calculations were Organoclay® amendments. Design options include placement of bulk Organoclay® and blending of Organoclay® with sand, with practical implications for each scenario. Limited swelling of Organoclay® is expected with dilute aqueous emulsions of NAPL (e.g., less than 1% NAPL in water), but Organoclay® can be subject to significant swelling and reduction of hydraulic conductivity when in contact with concentrated NAPL (Lee et al., 2012; CETCO, 2017). Table 2 summarizes the hydraulic conductivity of

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **3**   of   **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

Organoclay® PM-200 and PM-199 with water/NAPL as permeants and in their bulk or blended with sand applications.

As summarized in Table 2, hydraulic conductivity in dilute aqueous solutions is about 9.4×10^{-3} cm/sec for PM-200 (CETCO, 2017) and 0.14 cm/sec for PM-199 (Lee et al., 2012), whereas, the hydraulic conductivity after permeated with concentrated NAPL was notably lower, such as less than 4.3×10^{-7} cm/sec for PM-200 (CETCO, 2017) and 9.6×10^{-10} cm/sec for PM-199 (Lee et al., 2012). Attachment B to this calculation package provides additional details on swelling and hydraulic conductivity reductions of oleophilic clays.

Significant permeability reductions could lead to conditions which can challenge the integrity of the cap layer, such as: enhanced flow bypassing around the low permeability section, buildup of pressure below the cap, and possible formation of preferential flow paths. When Organoclay® is blended with sand at ratios less than or equal to 25%:75% (OC to Sand based on dry weight), swelling is moderated and hydraulic conductivity reductions are less affected compared to pure Organoclay® layer (CETCO, 2017; refer to Table 2). Because one of the design objectives of the oleophilic clay layer is not to hinder groundwater movement in areas with no potentially migrating NAPL, utilizing an Organoclay® and sand blend is advantageous since it dampens the issues concerning permeability reductions of the Organoclay® layer. Therefore, Organoclay® blended with sand was retained for evaluation of the oleophilic clay treatment layer.

Thickness and Composition Calculations

Oleophilic clay layer thickness and composition were calculated for Organoclay® PM-199 and PM-200 mixed with sand. The mass of Organoclay® per square foot area was calculated based on the mixing ratio, dry density of the sand, and amendments using Equation 1.

$$M_{OC} = \rho_{OC} * \left[\frac{T_{layer}}{1 + \frac{f_{sand}}{f_{OC}} * \frac{\rho_{OC}}{\rho_{sand}}} \right] \qquad (1)$$

Where:

   M_{OC} : mass of Organoclay® per unit area (psf);

   ρ_{oc} : dry density of Organoclay® (pcf);

   ρ_{sand} : dry density of sand (pcf);

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **4**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

f_{oc} : fraction of Organoclay® by dry weight (%);

f_{sand} : fraction of sand by dry weight (%); and

T_{layer} : thickness of Organoclay® layer (ft).

The associated NAPL sorption capacity of a given cap thickness and composition were calculated using Equation 2.

$$M_{NAPL} = M_{OC} * S_{NAPL} \qquad (2)$$

Where:

M_{NAPL} : Organoclay® layer NAPL mass sorption capacity (psf); and

S_{NAPL} : Organoclay® type specific unit NAPL sorption capacity ($lbs_{NAPL}/lbs_{Organoclay}$).

Table 3 summarizes the NAPL mass sorption capacity of the various Organoclay® layer thickness and compositions.

Oleophilic Clay Layer Performance Criteria

The expression of NAPL in native sediment pore space induced by sediment consolidation (primary and secondary) upon cap loading was evaluated in a NAPL expression desktop study (Geosyntec, 2017a; Attachment C to this calculation package). The volume of potentially expressing NAPL into the cap in non-ISS treatment locations was estimated to be between less than 0.0001 and 0.022 cu-ft NAPL/sq-ft of cap (based on predicted excess NAPL saturation greater than 20% within the top 1 feet of the cap). This total value is conservative since it does not take into consideration areas where ISS will be applied in RTA1, and NAPL expression rates anticipated in the TB4 pilot study area are estimated to be much lower (e.g., maximum NAPL expression rate of 0.002 cu-ft NAPL/sq-ft of cap).

Based on the measured NAPL density of 66.8 lbs/cu-ft, that is an average of data collected under PD-8 NAPL mobility investigation (Geosyntec, 2015b) and NAPL densities reported in the Feasibility Study Appendix A (CH2M, 2011b), NAPL expression of up to 1.5 lbs of NAPL/sq-ft of cap is anticipated in non-ISS treated locations in RTA1 and TB4. Therefore, the oleophilic clay layer design requires a NAPL sorption capacity higher than 1.5 lbs of NAPL/sq-ft of the cap, while minimizing the impacts on groundwater movement in the system. Additionally, oleophilic clay

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **5**   of   **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

layer performance criteria accounted for the constructability constraints (e.g., minimum thickness), and maintaining the hydraulic conductivity (e.g., blending with sand).

Granular Activated Carbon Layer

GAC treatment layer thickness and composition were evaluated using a one-dimensional (1D) numerical contaminant transport model that evaluates contaminant transport vertically from the underlying sediment (native sediments) through the cap and into the overlying water column.

Treatment layer modeling incorporated available Site-specific data as well as the findings from several pre-design investigations (e.g., PD-7, PD-12, and PD-17) to assess the long-term efficacy of the GAC treatment layer under a range of representative Site conditions. These inputs are described further in the Input Parameters and Assumptions section.

The CapSim v3.2a model (Reible Research Group, 2014; Lampert, 2010) was used for the simulation of contaminant transport in sediment and through the sediment cap. The CapSim model was selected due to its widespread acceptance and previous application for the Site (CH2M Hill, 2015). Dissolved-phase PAH breakthrough concentrations as a function of treatment layer thickness and composition were assessed relative to performance criteria and are discussed in the Model Results section.

Input Parameters and Assumptions

Representative input parameters were used with current understanding of Site conditions to determine the GAC treatment layer properties required to meet these criteria over the 100-year design life of the cap.

The mass flux model input parameters include chemical-specific sorption parameters, GAC treatment layer composition related parameters, system properties, and existing conditions of the Canal. The input parameters and assumptions used in the GAC treatment layer design are summarized in Table 4. The GAC treatment layer thickness and composition (i.e., ratio of activated carbon and sand) varied over each model run to simulate the lifetime of the GAC treatment layer under different design conditions.

Model Chemical Input Parameters

While NAPL and PAHs are the design target constituents for the cap treatment layer, the cap will also be protective for PCBs, metals, and several other contaminants through physical separation and sorption within the treatment layer. Naphthalene was selected to be the representative

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

constituent for the GAC treatment layer model simulation based on presence in the Canal and relatively higher water solubility and mobility when compared to other PAHs.

Although the model includes biological (e.g., biotransformations, decay) and geochemical reactions (e.g., chemical transformation) that can contribute to dissolved-phase concentration reductions within the treatment layer, naphthalene was conservatively assumed to undergo no reactive processes during the capping simulation. Additionally, source depletion was conservatively not assumed. The Site-specific Freundlich isotherm constants (K_F and $1/n$) were determined based on Phase 1 PD-17 testing (Geosyntec, 2016a).

Composition and Thickness

The GAC treatment layer design optimizes layer thickness and configuration of active (e.g., activated carbon) and passive (e.g., sand) capping materials to meet performance criteria.

For representative simulation of the GAC-based treatment layer, geotechnical and geochemical parameters were defined for the GAC, sand, and mixed compositions. These parameters included porosity, bulk density, fraction of organic carbon, tortuosity correction, hydrodynamic dispersivity, and dissolved organic matter correction. The GAC porosity and carbon bulk density were derived from the FiltraSorb 400 GAC product bulletin (CalgonCarbon, 2012), which is equivalent to the TIGG LLC GAC tested during Phase 1 PD-17 testing (TIGG LLC, personal communication, April 3rd, 2017), and the GAC carbon fraction was assumed to be 1. The sand porosity, bulk density, and organic carbon fraction were defined based on values commonly applied (Reible 2014), which were consistent with average literature values (Holtz et al., 2011). Mixed composition layers used weighted averages of these values based on the compositional fraction of each material.

The tortuosity correction used the Millington & Quirk derived factor, which is applicable to a wide range of grain sizes, and the hydrodynamic dispersivity was assumed to be one tenth of the layer thickness (Reible, 2014). The dissolved organic matter concentration was assumed to be zero as sorption to dissolved organic matter is inherently accounted for in the sorption data from PD-17.

Breakthrough is defined at the top of the treatment layer. It should be noted that the model set-up includes an arbitrary 4 in (10 cm) thick sand layer that is placed on top of the treatment layer and is not part of the actual cap design for the Canal. This arbitrary layer is recommended by the model developer and is needed to prevent numerical instability issues due to infinite dilution of dissolved-phase constituents on top of the cap treatment layer.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

System Properties

The Site-specific system properties including the groundwater upwelling rate were defined to evaluate model processes.

The Canal input groundwater upwelling rate was simulated for post-remedy conditions in TB4 using the groundwater model refined under work elements PD-7 and PD-12 (Geosyntec, 2015a; Geosyntec, 2016b). Specific discharge was exported from the groundwater model for input into the treatment layer transport model. The groundwater model simulated soft sediment removal, hot-spot removal/backfill of native alluvial sediment and capping application in TB4. Therefore, location-specific groundwater upwelling rates in 15 x 15-ft grid cells were used in the model simulations. Although the Canal is tidally influenced, the upwelling groundwater flow is simulated as steady flow to allow for constant upwelling rates, which represent a conservative condition. The distribution of simulated, post-remedy groundwater specific discharge in the TB4 Pilot Study area is provided in a separate calculation package focused on the groundwater modeling. Model predicted groundwater upwelling rates in TB4 Pilot Study area ranges from 17 to 780 cm/yr (median flow rate of 255 cm/yr).

The processes of bioturbation was not included in the treatment layer modeling since the treatment layer will be located beneath armoring and ecological layers, which will physically isolate benthic biota from the treatment layer of the cap. Therefore, it is assumed that bioturbation will be negligible within the treatment layer. Similarly, consolidation of underlying native sediment and the associated transient consolidation induced dissolved-phase naphthalene flux was evaluated for a maximum of 3.5 inches of settlement and is not included in the treatment layer design since it amounted to less than 0.5% of annual advective naphthalene flux.

Initial and Boundary Conditions

Initial porewater concentrations within the GAC treatment layer are assumed to be zero since clean capping material is to be employed. The naphthalene porewater concentrations were selected based on porewater and groundwater data collected during: (i) PD-8: NAPL Mobility Investigation Report (Geosyntec, 2015b); (ii) Gowanus Canal Remedial Investigation (CH2M Hill, 2011a); and (iii) the former 5th Turning Basin Site Investigation. Table 5 summarizes the samples, sampling locations and naphthalene concentrations measured in these samples. Additionally, sediment sample location GC-SD87 was incorporated into the list of samples because of observed NAPL impacts at this location. No associated groundwater or porewater concentration was measured at this location, therefore the highest naphthalene groundwater concentration measured in 5th Turning Basin Site Investigation was used (670 ug/L).

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

The data summarized in Table 5 were used to prepare Thiessen polygons of naphthalene porewater/groundwater concentration distribution (Figure 1). Location-specific naphthalene flux values in 15 x 15-ft grid cells were calculated using 2 times the naphthalene porewater/groundwater concentrations as delineated in these Thiessen polygons and groundwater upwelling rates as estimated by the groundwater model simulation. The factor of 2 was applied to the measured naphthalene concentrations to account for uncertainty in the concentrations, the groundwater simulation results, and the treatment layer results. Figure 2 presents location-specific naphthalene flux values grouped into three categories (e.g., less than median; median to 95th percentile, and 95th percentile to maximum). As presented in Figure 2, location-specific naphthalene flux ranged from less than 1 mg/yr to 5,038 mg/yr. A large data gap existed between 20 mg/yr to 1,446 mg/yr which effectively bifurcated the data.

Finally, to avoid constructability issues, the minimum GAC treatment layer thickness was set to 4 inches and the minimum GAC content was set to 5%.

GAC Treatment Layer Performance Criteria

Dissolved PAH breakthrough concentrations as a function of treatment layer thickness and composition were evaluated against performance criteria for the Canal. More specifically, treatment layer longevity and protectiveness was evaluated by comparing dissolved-phase steady-state discharge concentrations from the treatment layer with final chronic value for naphthalene (193.5 µg/L). Final chronic values are ecological risk based numbers calculated from the target lipid model and are presented in the 2011 Feasibility Study (USEPA, 2003; CH2M Hill, 2011b).

To evaluate performance, the point of compliance was selected as the top of the GAC treatment layer. For the TB4 pilot study area design, the concentration of porewater as it exits the top of the GAC treatment layer is compared to the final chronic values to determine the time elapsed to breakthrough and cap design life. Breakthrough is defined as reaching naphthalene porewater concentrations greater than the final chronic values at the top of the GAC treatment layer. Breakthrough time (in years) is compared to the 100-year design life target for the GAC treatment layer to identify viable thicknesses and compositions. The time to breakthrough for simulated GAC treatment layers is summarized in Table 6.

Additionally, it is noteworthy that a geotechnical evaluation of the cap treatment materials was performed to ensure the amendments evaluated for chemical performance did not present any geotechnical stability issues (refer to Attachment B).

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **9** of **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

RESULTS

Oleophilic Clay Layer

As summarized in Table 3, 4-inch to 6-inch Organoclay® layer thicknesses with 10% to 25% (by dry weight) Organoclay® content were evaluated. The 6-inch 25% Organoclay® and 75% sand blend provided comparable NAPL sorption capacity (e.g., 15.7 lbs$_{NAPL}$/sq-ft refer to Scenario 5 in Table 3) to 2-inch bulk delivery option evaluated (15 lbs$_{NAPL}$/sq-ft refer to Scenario 1 in Table 3), which does not account for physical isolation of the NAPL by the additional sand material (refer to Table 1 for physical sequestration of NAPL via silica sand). This sorption capacity of the 6-inch 25% Organoclay and 75% sand blend is more than 10-fold greater than the maximum calculated NAPL expression that can potentially be mobilized by porewater expression after cap loading.

To avoid significant reductions in hydraulic conductivity of the oleophilic clay layer as highlighted in the literature (refer to Table 2; Lee et al., 2012; CETCO, 2017), a 6-inch oleophilic clay layer with 25% Organoclay PM-200 and 75% sand (by dry weight) was selected for TB4 pilot study area.

Granular Activated Carbon Layer

As presented in Figure 2, a small area on the eastern end of TB4 adjacent to the 3rd Avenue Bridge (Cap Type II) is predicted to have relatively higher flux values (up to 5,038 mg/year), while the remainder of TB4 (Cap Type I) is predicted to have relatively lower flux values (up to 20 mg/year). Hence, two different cap treatment layer compositions were developed for the TB4 pilot study area.

As summarized in Table 6, for the small area on the eastern end of TB4 (Cap Type II) cap thickness and composition were governed by the relatively higher naphthalene flux. A 4-inch 40% GAC + 60% Sand (by dry weight) layer is estimated to reach breakthrough in 103 years based on the 2 times the location-specific flux values (5,038 mg/year; refer to Drawings C-2 and C-3).

For the remainder of the TB4 pilot study area (Cap Type I), where location-specific flux values were relatively low (up to 20 mg/year), the GAC treatment layer thickness and composition were governed by the minimum cap thickness and GAC content based on constructability. The resulting 4-inch 5% GAC + 95% Sand (by dry weight) layer is estimated to reach breakthrough after 200 years (refer to Drawings C-2 and C-3).

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **10** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

SUMMARY AND CONCLUSIONS

Based on the calculations presented herein, two cap treatment layer types will be used in the 4th Turning Basin pilot study area. The Cap Type II treatment layer (small area on the eastern end of TB4) will consist of 6-inch Organoclay PM-200 + Sand layer with 25% Organoclay PM-200 and 75% sand, and 4-inch GAC + Sand layer with 40% GAC and 60% sand (percent by dry weight). The Cap Type I treatment layer (remainder of the TB4 pilot study area) will consist of 6-inch Organoclay PM-200 + Sand layer with 25% Organoclay PM-200 and 75% sand, and 4-inch GAC + Sand layer with 5% GAC and 95% sand (percent by dry weight).

The resulting cap treatment layer will meet final chronic value performance criteria over a 100-year design life and will be able to adsorb up to 15.7 pounds of potential upwardly mobile NAPL per square feet of the cap, which is 10 times greater than the anticipated NAPL expression rate.

As highlighted in the discussion of results, these initial findings reflect a conservative thickness and composition for the cap treatment layer based on the current understanding of Site conditions. The cap treatment layer thicknesses and compositions are primarily governed by constructability, with the exception of the small area at the eastern end of TB4.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **11** of **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

REFERENCES

Aqua Technologies of Wyoming, Inc. Product Specifications ET-1 Activated Clay. Aqua Technologies of Wyoming Inc., 1465 W. Scenic Street, Casper, WY 82601. 2016.

AquaBlok. Product Specifications, AquaGate+PAC. AquaBlok, Ltd, 175 Woodland Avenue, Swanton, OH, 43558. 2016a.

AquaBlok. Technical Specifications, AquaGate + Organoclay®. AquaBlok, Ltd, 175 Woodland Avenue, Swanton, OH, 43558. 2016b.

CalgonCarbon. Product Bulletin, Filtrasorb® 400, Granular Activated Carbon. Calgon Carbon Corporation, 500 Calgon Carbon Drive, Pittsburgh, PA, 15205. 2012.

CETCO. Technical Data Organoclay® PM-200. CETCO, 2870 Forbs Avenue, Hoffman Estates, IL, 60192. 2016a.

CETCO. Technical Data Organoclay® PM-199. CETCO, 2870 Forbs Avenue, Hoffman Estates, IL, 60192. 2016b.

CETCO. Technical Reference NAPL Sorption Capacity and Permeability of Organoclay/Sand Mixture. CETCO, 2870 Forbs Avenue, Hoffman Estates, IL, 60192. 2017.

CH2M HILL. *Draft Feasibility Study, Gowanus Canal*. December, 2011a.

CH2M HILL. *Draft Feasibility Study, Gowanus Canal*. December, 2011b.

CH2M HILL. *Technical Memorandum; Sediment Cap Treatment Layer Analysis, Gowanus Canal Superfund Site, Brooklyn, New York*. October, 2015.

Geosyntec. *Draft PD-7: Groundwater Upwelling Investigation Report*. October, 2015a.

Geosyntec. *Draft PD-8: NAPL Mobility Investigation Report*. October, 2015b.

Geosyntec. *Draft PD-12: Groundwater Model Update Report*. 2016b.

Geosyntec. *Draft PD-17: Treatability Testing of Active Cap Layer Materials, Phase 1 – Screening of Amendments Report*. October, 2016a.

Geosyntec. *Draft Potential for Consolidation-Induced DNAPL Expression at the Gowanus Canal Superfund Site Report*. 2017a.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **12** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

Geosyntec. *Draft 5th Street Turning Basin Pre-Design Investigation Report.* 2017b.

Holtz, R.D., Kovacs, W.D., Sheahan, T.C. *An Introduction to Geotechnical Engineering.* Pearson Education, Upper Saddle River, NJ. 2011

Lampert, D.J. *An assessment of the design of in-situ management approaches for contaminated sediments*, PhD Thesis. University of Texas at Austin, Austin, TX, USA. 2010.

Lee, S., Oren, A.H., Benson, C.G., Dovantzis, K. 2012. Organoclays as Variably Permeable Reactive Barrier Media to Manage NAPLs in Ground Water. *ASCE Journal of Geotechnical and Geoenvironmental Engineering.* 138(2):115-127.

Meric, D., Barbuto, S., Sheahan, T.C., Shine, J.P., Alshawabkeh, A.N. 2014. Benchscale Assessment of the Efficacy of a Reactive Core Mat to Isolate PAH-Spiked Aquatic Sediments. *Soil and Sediment Contamination: An International Journal.* 23(1):18-36. DOI: 10.1080/15320383.2013.772093

Reible, D.D. *Organoclay® Laboratory Study – McCormick & Baxter.* Report to State of Oregon Department of Environmental Quality. September 2005.

Reible, D.D. *Processes, Assessment and Management of Contaminated Sediments*, Chapter 12. Springer Science + Business Media, New York. 2014.

Reible Research Group. *CAPSIM Version 2.8. Release Date October 3, 2014.* https://www.depts.ttu.edu/ceweb/groups/reiblesgroup/downloads.html. Accessed September, 2016.

TIGG LLC. Personal Communication (2017, April 3rd). Phone Call.

TIGG LLC. Technical Specifications TIGG OMC-P Oil Removal Media. TIGG LLC, 1 Willow Avenue, Oakdale, PA, 15071. 2016.

USEPA. *Equilibrium Partitioning Sediment Benchmarks (ESBs) for the Protection of Benthic Organisms: Procedures for the Determination of the Freely Dissolved Interstitial Water Concentrations of Nonionic Organics.* December, 2012.

USEPA. *Record of Decision – Gowanus Canal Superfund Site, Brooklyn, Kings County, New York.* September, 2013.

Geosyntec ▷
consultants

Beech and Bonaparte ▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   13   of   101

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

TABLES

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **14** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

Table 1. Oleophilic clay layer thickness calculations input parameters

Vendor	Control	CETCO	CETCO	TIGG	Aqua Technologies of Wyoming	AquaBlok
Oleophilic Clay Type	Silica Sand	Organoclay® PM-200	Organoclay® PM-199	OMC-P	ET-1 Activated Clay	AquaGate™ + Organoclay®[8]
Parameter	**Values**					
Chemical Parameters[1]						
NAPL Sorption						
Replicate 1	45%	191%	171%	72%	79%	63%
Replicate 2	45%	177%	160%	72%	82%	63%
Replicate 3	44%	173%	167%	72%	62%	63%
Mean	45%	180%	166%	72%	74%	63%
Standard Deviation	1%	9%	6%	0%	11%	0%
Physical Parameters[2,3,4,5,6,7]						
Bulk Density (pcf)	N/A	50	50	58	46	80
Reactive Core Mat Mass per Area (psf)	N/A	0.8	0.8	N/A	N/A	N/A
Min Permeability (cm/sec)	N/A	$1x10^{-3}$	$1x10^{-3}$	NP	NP	$1x10^{-5}$

Notes:

1. PD-17: "Treatability Testing of Active Cap Layer Materials" (Geosyntec, 2016a)

2. Technical Data Organoclay PM-200 (CETCO, 2016a)

3. Technical Data Organoclay PM-199 (CETCO, 2016b)

4. Technical Data Reactive Core Mat (CETCO, 2016c)

5. Technical Specifications TIGG OMC-P Oil Removal Media (TIGG, 2016)

6. Product Specifications ET-1 Activated Clay (Aqua Technologies of Wyoming, 2016)

7. Technical Specifications AquaGate + Organoclay® (AquaBlok, 2016)

8. Modified from PD17 to reflect 30% of organoclay by mass

N/A Not applicable

NP Not provided by the vendor

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

Table 2. NAPL mass sorption capacity of oleophilic clay layer configurations

Oleophilic Clay Type	Permeant	Composition (% Weight)		Hydraulic Conductivity (cm/sec)	Reference
		Organoclay®	Sand		
PM-199	Water[1]	100%	0%	0.14	Lee et al. (2012)
	NAPL	100%	0%	7.60E-10	
	NAPL	10%	90%	2.60E-06	
	NAPL	25%	75%	8.60E-09	
	NAPL	50%	50%	2.80E-10	
PM-200	Water[1]	100%	0%	9.40E-03	CETCO (2017)
	Water[1]	10%	90%	2.15E-03	
	NAPL	100%	0%	< 4.30E-07	
	NAPL	10%	90%	1.90E-05	
	NAPL	20%	80%	4.90E-06	
	NAPL	25%	75%	5.80E-06	
Sand	NAPL	0%	100%	4.10E-05	Lee et al. (2012)

Notes:
1. Clean water was used as permeant to mimic dilute aqueous solution

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

Table 3. NAPL mass sorption capacity of oleophilic clay layer configurations

Scenario	Treatment Layer Thickness		Composition (% By Weight)[1]		Organoclay Volume (cu-ft/sq-ft)[2,3]	Organoclay Mass (psf)	NAPL Mass Sorption Capacity (psf)[4,5]
	(in)	**(cm)**	**Organoclay®**	**Sand**			
1	2	5.08	100%	0%	0.167	8.33	15.0
							13.8
2	4	10.16	10%	90%	0.05	2.52	4.5
							4.2
3	4	10.16	25%	75%	0.116	5.8	10.4
							9.6
4	6	15.24	10%	90%	0.075	3.77	6.8
							6.3
5	**6**	**15.24**	**25%**	**75%**	**0.174**	**8.7**	**15.7**
							14.4

Notes:

1. Oleophilic clay layer composition values are based on dry weight ratios
2. Sand dry density assumed to be 80 psf in calculations
3. Organoclay® dry density assumed to be 50 psf in calculations (CETCO, 2016a,b)
4. NAPL sorption capacity for Organoclay® PM-200 of 1.8 $lbs_{NAPL}/lbs_{Organoclay}$ (see Table 1) used in calculations
5. NAPL sorption capacity for Organoclay® PM-199 of 1.66 $lbs_{NAPL}/lbs_{Organoclay}$ (see Table 1) used in calculations

Bold – Selected oleophilic clay layer thickness and composition for TB4 Pilot Study Area

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **17** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**

CC: **JAW** Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Table 4. CapSim model input parameters

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$, CAS 91-20-3	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F $(\mu g/kg/(\mu g/L)^N)$	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Matrix	GAC	Sand
Porosity	0.58	0.5
Bulk Density (g/cm^3)	0.54	1.25
Organic Carbon Fraction	1	0.001
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	0.1 * Layer Thickness	0.1 * Layer Thickness
Dissolved Organic Matter Concentration (mg/L)	0	0
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow Alternative (cm/yr)	10 to 376	
Bioturbation	None	
Consolidation	None	
Initial and Boundary Conditions		
Treatment Layer Boundary Layer Conditions	Uniform	
Treatment Layer Initial Concentration (µg/L)	0	
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration	
Underlying Pore Water Initial Concentration (µg/L)	200 to 1,340 µg/L (factors 2 x location-specific flux)	

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

Table 5. Porewater and groundwater concentrations used to evaluate the underlying pore water boundary condition concentration (µg/L)

Location ID	Sample ID	Easting	Northing	Naphthalene Concentration (µg/L)	Media	Study
MW-37	GC-MW37I	633517.5	671258.6	0.48	Groundwater (Intermediate)	Remedial Investigation[1]
MW-37	D-07262010-01	633517.5	671258.6	0.44	Groundwater (Intermediate)	Remedial Investigation[1]
MW-38	GC-MW38I	633787.6	671082.2	2.1	Groundwater (Intermediate)	Remedial Investigation[1]
MW-39	DUP-U-01	--	--	41	Groundwater (Intermediate)	TB5 Investigation[2]
MW-39	MW-39-I	--	--	670	Groundwater (Intermediate)	TB5 Investigation[2]
MW-A-I	MW-A-I	--	--	0.25	Groundwater (Intermediate)	TB5 Investigation[2]
MW-E-I	MW-E-I	--	--	170	Groundwater (Intermediate)	TB5 Investigation[2]
MW-I-I	MW-I-I	--	--	110	Groundwater (Intermediate)	TB5 Investigation[2]
4TB0450-A	NS-SEDMI-4TB0450-A-17-22-WG-151002	633589.8	671100.9	0.28	Porewater	PD8 Investigation[3]
4TB0450-A	NS-DUP-01-WG-151002	633589.8	671100.9	0.42	Porewater	PD8 Investigation[3]
GC-SD87	N/A	633828.0	670945.8	670[4]	Sediment	Remedial Investigation[1]

Notes:

1. CH2M Hill. 2011. Gowanus Canal Draft Remedial Investigation Report. January, 2011.

2. Geosyntec. 2017b. Former 5th Turning Basin Site Investigation.

3. Geosyntec. 2015b. Draft PD-8: NAPL Mobility Investigation Report.

4. Sediment sample with NAPL impacts. Although there is no associated porewater or groundwater sample at this location, groundwater concentration measured in MW-39-I were adopted to address observed NAPL impacts.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **19** of **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Table 6. Model simulation results for treatment layer thickness and composition

Cap Type	Simulation	Groundwater Upwelling (cm/yr)	Naphthalene Concentration (µg/L)	Naphthalene Flux (mg/yr/m²)	Treatment Layer Thickness (in)	Treatment Layer Thickness (cm)	Layer Composition (% by dry weight) GAC	Layer Composition (% by dry weight) Sand	Time to Breakthrough (years)
I	**1**	**10**	**200**	**20**	**4**	**10.16**	**5%**	**95%**	**> 200**
I	2	10	200	20	4	10.16	1%	99%	> 200
II	3	376	1,340	5,038	4	10.16	10%	90%	26
II	4	376	1,340	5,038	4	10.16	12.5%	87.5%	32
II	5	376	1,340	5,038	4	10.16	20%	80%	51
II	6	376	1,340	5,038	4	10.16	25%	75%	65
II	7	376	1,340	5,038	4	10.16	30%	70%	77
II	8	376	1,340	5,038	4	10.16	35%	65%	90
II	**9**	**376**	**1,340**	**5,038**	**4**	**10.16**	**40%**	**60%**	**103**

Notes:
1. Cap Type I is targeted to the western portion of the TB4 (refer to Drawings)
2. Cap Type II is targeted to the eastern portion of the TB4 adjacent to 3rd Avenue Bridge (refer to Drawings)
3. Simulation 2 is screened out based on design assumptions and Cap Type I GAC treatment layer selection was governed by constructability constraints
Bold – Represent the selected GAC treatment layer thickness and compositions for Cap Types I and II
See Attachment A for model input parameters and results for each simulation

Geosyntec consultants	Beech and Bonaparte engineering p.c. *an affiliate of Geosyntec Consultants*						
CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**
Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**		Project No:	**HPH106A**

FIGURES

Legend

- Porewater & Groundwater Sample Locations

Naphthalene Concentrations (ug/L)

- Less than 100 ug/L
- 100 to 500 ug/L
- 500 to 1,000 ug/L
- 1,000 to 2,000 ug/L
- 2,000 to 6,300 ug/L

230   115   0   230 Feet

Porewater and Groundwater Naphthalene Concentration Thiessen Polygon

Gowanus Canal, Brooklyn, NY

Gowanus Canal Remedial Design Group

Geosyntec consultants

Beech and Bonaparte engineering p.c.
an affiliate of Geosyntec Consultants

Figure 1

Ewing, NJ   May 2017

HPH106A/Appendix B9 - Treatment Layer Design Evaluation

RTA 2

Naphthalene Flux Based on Thiessen Polygons

Gowanus Canal, Brooklyn, NY

Legend

Naphthalene Flux Based on 2 x Thiessen Polygon Concentrations

- Less than 2.9 mg/year
- 2.9 to 20 mg/year
- 20 to 5,038 mg/year

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Notes:
- Naphthalene flux values were calculated based on location-specific groundwater upwelling rates and the 2x the measured concentration within the associated Thiessen Polygon in 4th Turning Basin

Gowanus Canal Remedial Design Group

Geosyntec consultants

Beech and Bonaparte engineering p.c.
an affiliate of Geosyntec Consultants

Ewing, NJ   May 2017

Figure 2

HPH106A/Appendix B9 - Treatment Layer Design Evaluation

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

ATTACHMENT A MODEL SIMULATION RESULTS

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **24** of **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

SIMULATION 001

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F $(\mu g/kg/(\mu g/L)^N)$	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	5% GAC 95%Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.5
Bulk Density (g/cm^3)	1.25	1.21
Organic Carbon Fraction	0.001	0.023
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	10	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **25**   of   **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	200

Model Results

Breakthrough (years)   > 200

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
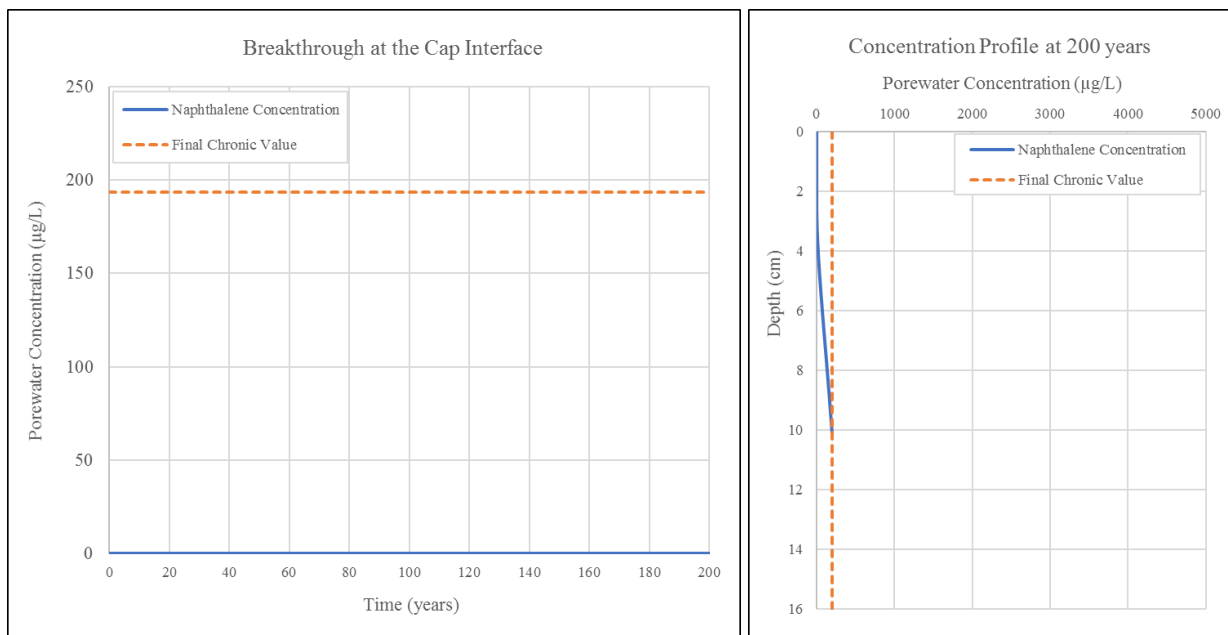May 2017

Page **26** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

SIMULATION 002

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F $(\mu g/kg/(\mu g/L)^N)$	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	1% GAC 99%Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.50
Bulk Density (g/cm^3)	1.25	1.24
Organic Carbon Fraction	0.001	0.005
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	10	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
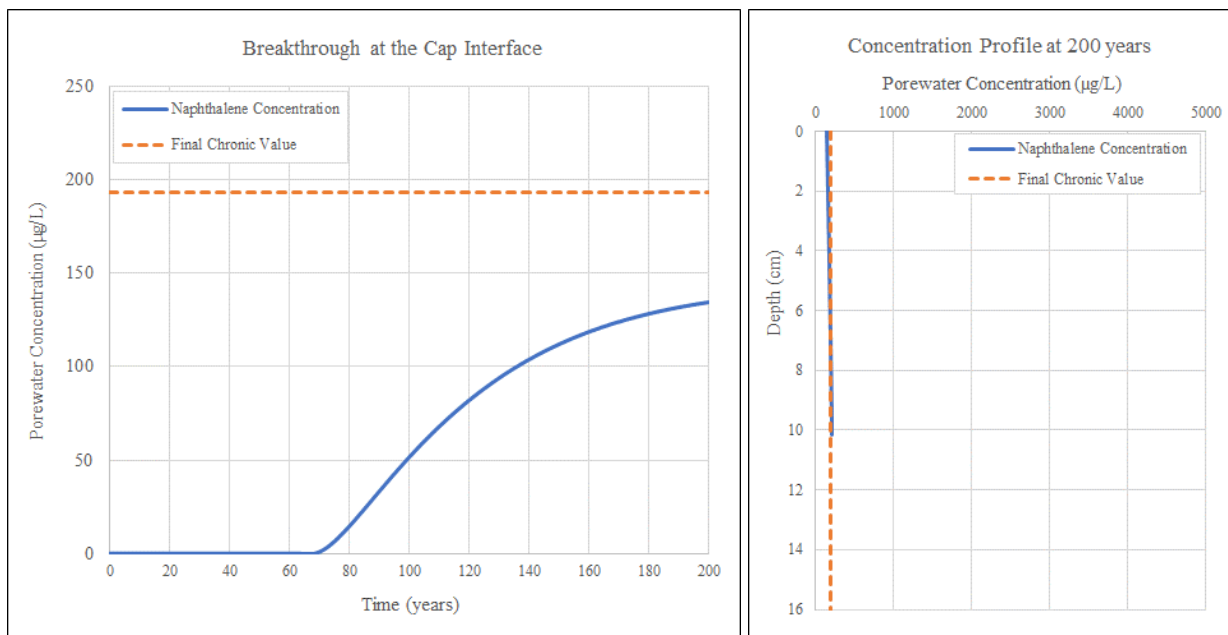*an affiliate of Geosyntec Consultants*

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	200

Model Results

Breakthrough (years)   > 200

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

SIMULATION 003

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F (µg/kg/(µg/L)^N)	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	10% GAC 90% Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.51
Bulk Density (g/cm^3)	1.25	1.18
Organic Carbon Fraction	0.001	0.047
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **29**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**
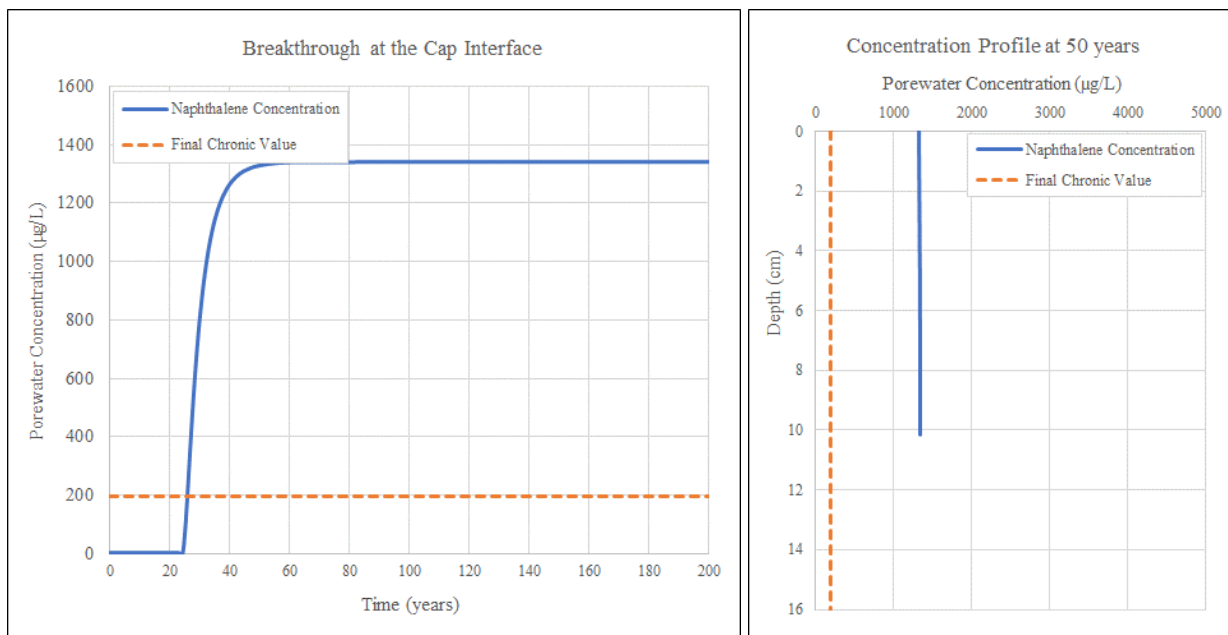
Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   26

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

SIMULATION 004

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F (µg/kg/(µg/L)^N)	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	12.5% GAC 87.5% Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.51
Bulk Density (g/cm^3)	1.25	1.16
Organic Carbon Fraction	0.001	0.059
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
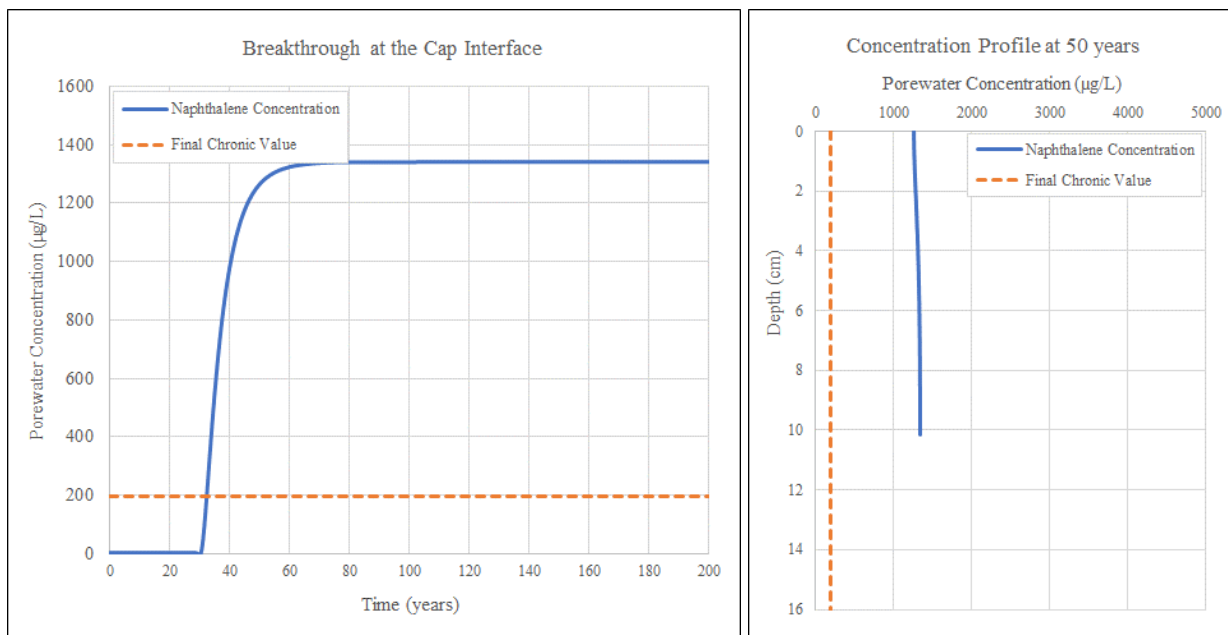*an affiliate of Geosyntec Consultants*

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   32

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

SIMULATION 005

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F $(\mu g/kg/(\mu g/L)^N)$	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	20% GAC 80% Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.52
Bulk Density (g/cm^3)	1.25	1.11
Organic Carbon Fraction	0.001	0.098
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte ▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**
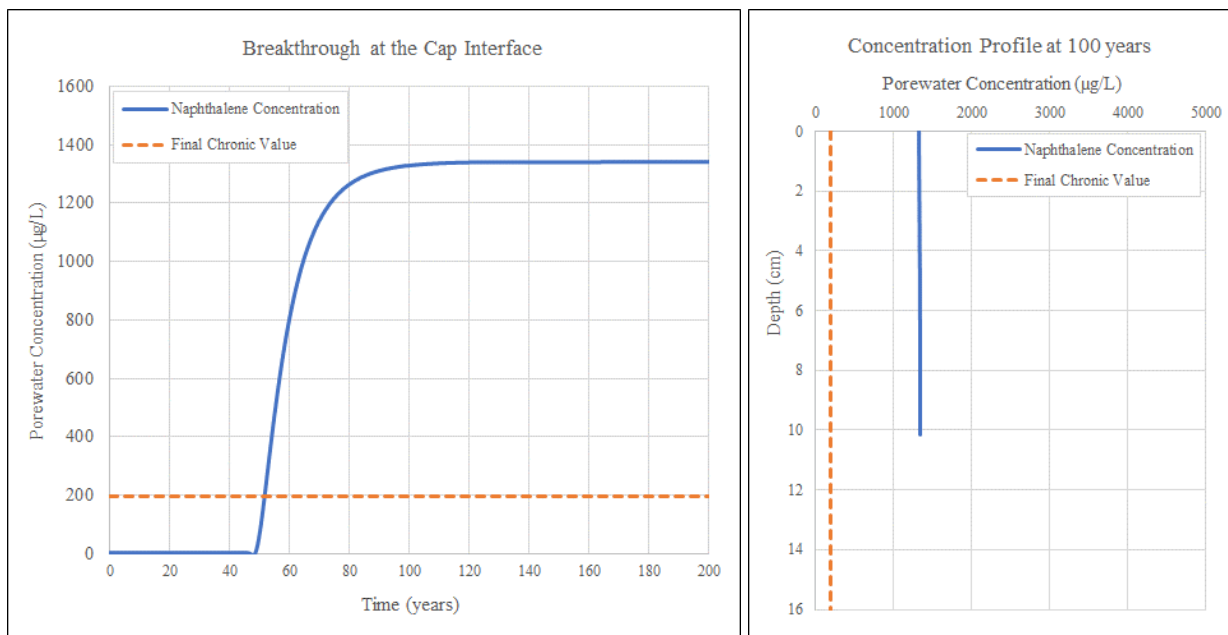
Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   51

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

SIMULATION 006

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F (µg/kg/(µg/L)^N)	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	25% GAC 75% Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.52
Bulk Density (g/cm^3)	1.25	1.10
Organic Carbon Fraction	0.001	0.127
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   65

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **36** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

SIMULATION 007

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F $(\mu g/kg/(\mu g/L)^N)$	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	30% GAC 70% Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.52
Bulk Density (g/cm^3)	1.25	1.04
Organic Carbon Fraction	0.001	0.157
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   77

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **38** of **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

SIMULATION 008

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F $(\mu g/kg/(\mu g/L)^N)$	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	35% GAC 65%Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.53
Bulk Density (g/cm^3)	1.25	1.002
Organic Carbon Fraction	0.001	0.19
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

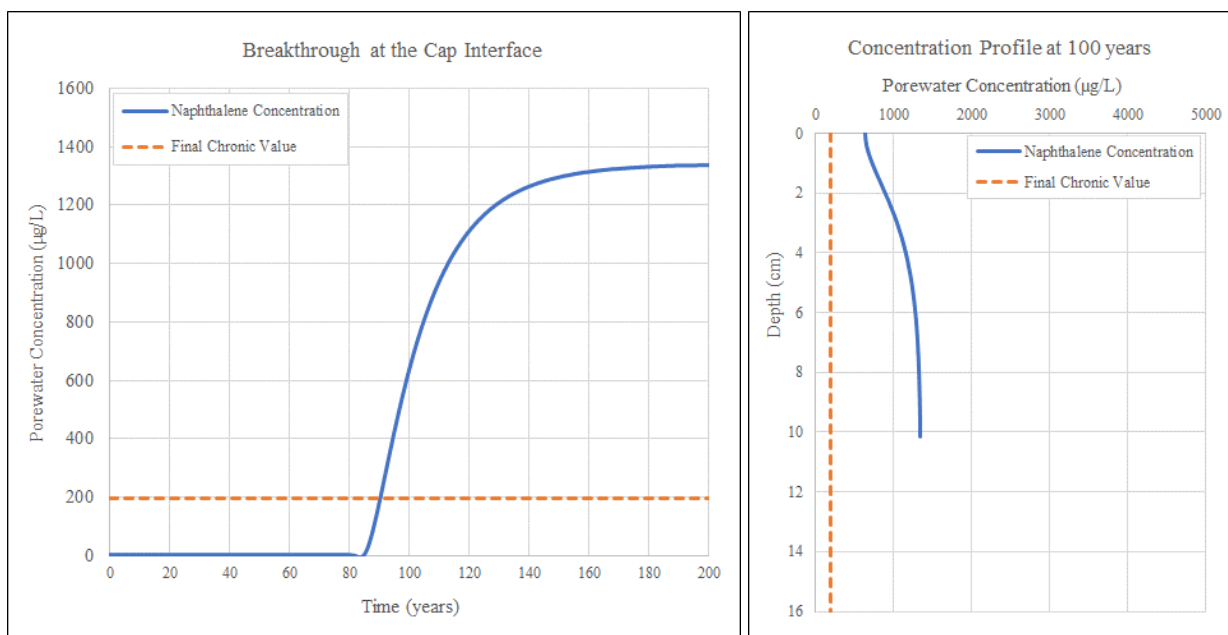Page   **39**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   90

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

SIMULATION 009

Model Inputs

Parameter	Values	
Chemical-Specific Parameters		
Chemical	Naphthalene, $C_{10}H_8$	
Material	GAC	Sand
Sorption Isotherm	Freundlich	Linear, K_d Specified
Isotherm Coefficient, K_F (µg/kg/(µg/L)^N)	1250714.1	-
Isotherm Coefficient, K_d (L/kg)	-	0.00
Isotherm Coefficient, N	0.45	-
Kinetic Options	Equilibrium	Equilibrium
Kinetic Processes	None	None
Cap Composition Parameters		
Layer	Layer 1	Layer 2
Thickness (cm)	10.0	10.16
Composition	100% Sand	40% GAC 60% Sand
Matrix	Sand	GAC + Sand
Porosity	0.5	0.53
Bulk Density (g/cm^3)	1.25	0.97
Organic Carbon Fraction	0.001	0.224
Tortuosity Correction	Millington & Quirk	Millington & Quirk
Hydrodynamic Dispersivity (cm)	1.00	1.016
Dissolved Organic Matter Concentration (mg/L)	0.00	0.00
System Properties		
Upwelling Groundwater Flow Type	Steady Flow	
Upwelling Groundwater Flow (cm/yr)	376	
Bioturbation	None	
Consolidation	None	
Initial Conditions		

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

Benthic Surface Boundary Layer Conditions	Mass transfer, Fixed concentration
Benthic Surface Concentration (µg/L)	0.00
Treatment Layer Boundary Layer Conditions	Uniform
Treatment Layer Initial Concentration (µg/L)	0.00
Underlying Sediment Boundary Layer Conditions (µg/L)	Fixed concentration
Underlying Sediment Initial Concentration (µg/L)	1,340

Model Results

Breakthrough (years)   103

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

ATTACHMENT B GEOTECHNICAL EVALUATION OF CAP AMENDMENTS

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**		Project No:	**HPH106A**

INTRODUCTION

The Gowanus Canal Superfund Site (Site), is a tidally influenced waterbody in Brooklyn, New York consisting of a 1.8-mile Canal and associated turning basins (herein referred to collectively as the Canal). The selected remedy in the 2013 Record of Decision (ROD) for the Site (EPA, 2013) includes, in part, dredging the entire layer of soft sediment, in-situ stabilization in select areas, and construction of a multilayered cap in the Canal to isolate and prevent the migration of polycyclic aromatic hydrocarbons (PAHs) and residual non-aqueous phase liquid (NAPL) from the newly exposed native sediments. The general cap configuration as described in the ROD consists of an armor layer, an isolation layer and an active treatment layer. The ROD described the treatment layer (1-foot (ft) in RTA1 and RTA2, and 0.5-ft in RTA3) as conceptually consisting of an oleophilic clay-sand mixture, with the exact configuration to be determined during the remedial design. Preliminary evaluations of cap layers suggest the treatment layer will differ from what was described in the ROD based on the Site conditions observed during pre-design investigations. Additionally, blended layers (e.g., mixing amendments with sand) will potentially be utilized to the extent practical to mitigate geotechnical issues.

This memo presents the results of a desktop study conducted to evaluate the geotechnical properties of various anticipated cap treatment layer amendments to better characterize the potential effect distinct treatment layers could have on armor layer and cap constructability, stability, and ultimately performance. The scope of the study assumed that the anticipated cap treatment layer amendments could include: (i) oleophilic clay (herein referred to as organoclay); (ii) Organoclay-Reactive Core Mat (OC-RCM); (iii) granular activated carbon (GAC); and (iv) sand/GAC mixtures. The geotechnical properties discussed in this paper, based on available technical literature, include: (i) index properties; (ii) shear strength; (iii) hydraulic conductivity; and (iv) consolidation parameters. The study included collection of pertinent amendment literature data, assumptions on site-specific loading from the cap layers, and basic calculations for compressibility of cap amendments.

ORGANOCLAY

Introduction

Organoclays are composites of organic matter and clay minerals. They are formed by replacing the naturally occurring inorganic cations (e.g., Na^+, Ca^{2+}) found in clays with organic cations.

| | | | | | | | | HPH106A |
| Treatment Layer Design Evaluation |
| Revision 0 |
| May 2017 |

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

Page   **44**   of   **101**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

Bentonite, primarily composed of montmorillonite, is the clay that is often used in the manufacture of organoclay. Quaternary alkylammonium cations (QACs) which are also referred to as quaternary amine cations are commonly used as exchange cations in Montmorillonite [Bate et al., 2014]. By exchanging the nitrogen end of a QAC onto the surface of clay, the clay becomes organically modified and is organophilic and hydrophobic [Lagaly, 1984].

When organoclay is placed in water, the ends of the amine chains are activated and standup causing pillaring of the layered clay particles. The ends of the amine chains that are suspended in the water react with the organics in the water and will dissolve or partition into large organic compounds such as sparingly soluble chlorinated hydrocarbons [Mortland et al., 1986]. The QAC can be chosen with different structures to optimize the chemical or mechanical behavior of the resulting organoclay. By targeting a percentage of clay's cation exchange capacity (CEC) for replacement, the total organic carbon content, or the amount of cation on the clay surface, can be carefully controlled.

Organoclays are used as sorbents in industrial operations or for hydraulic and sorptive barriers for organic compounds in geotechnical engineering [Benson et al., 2014]. This is due to their capacity to sorb organic compounds and their potential for low hydraulic conductivity when solvated by an organic liquid [Lo and Yang, 2001; Smith et al. 2003; Lorenzetti et al. 2005; Lee et al. 2012]. For example, Lee et al. [2012] describe an application where organoclay is used as the reactive medium in a vertical variably permeable reactive barrier (VPRB) to block the flow of creosote NAPL, but allow free flow of water while sorbing organic compounds dissolved in the water phase. In the presence of organic liquids, organoclays can behave in a manner similar to sodium bentonite contacted with water, exhibiting high plasticity, swelling, and low hydraulic conductivity [Lee et al. 2012]. Swelling and hydraulic conductivity differ between organic compounds in contact with the organoclay and the type of organic cation bound to the mineral surface.

The geotechnical properties of organoclays vary considerably based on the QAC used, clay used, amount of cation exchanged, and size of the cation [Burns et al., 2006; Bate et al., 2014].

Geotechnical Properties of Organoclays

Lee et al. [2012] and Dovantzis [2009] report the grain size distribution (GSD) of three commercially available organoclays. The organoclays used in their study were obtained from CETCO (organoclay: PM-199), Aqua Technologies Inc. (organoclay: ET-1), and Biomin, Inc. (organoclay: EC-199). Figure B-1(a) shows the GSD of the three organoclays as reported in Lee

Geosyntec▷

consultants

Beech and Bonaparte▷

engineering p.c.

an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **45** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

et al. [2012] and Dovantzis [2009]. Figure B-1(b) shows the GSD of CETCO PM-199 as indicated from technical data specifications [CETCO, 2014a]. The technical specifications of the ET-1 and EC-199 organoclays could not be obtained. Results from Figures B-1(a) and B-1(b) indicate that the three organoclays consist of sand-sized particles with particle size ranging from 0.25 to 2.0 mm. Compared to organoclays ET-1 and EC-199, PM-199 is finer and has a more uniform gradation.

Table B-1 summarizes the specific gravity, organic content and hydraulic conductivity to water of the three above mentioned organoclays. It can be observed that these organoclays have a low specific gravity which decreases with increasing organic content. The addition of the organic cations to the clay creates a hydrophobic phase that reduces the ability of the clay to swell in the presence of water, and consequently the water permeability of the organoclays is high relative to equivalent swelling clay. This results in a high hydraulic conductivity of organoclays to water as shown in Table B-1. Hydraulic conductivity of organoclays to NAPL and time effects on hydraulic conductivity of organoclays are discussed later in this section.

Bate [2010] and Burns et al. [2006] investigated the properties of quaternary ammonium cations and quantified their engineering effects on clays as functions of the molecular structure and cation loading. Results from these investigators indicated that the geotechnical properties (i.e., specific gravity, Atterberg limits, hydraulic conductivity, consolidation properties and shear strength) are influenced by the cation size, cation packing density and organic content of the organoclay.

Bate [2010] performed various geotechnical tests on five organobentonites (organoclays) synthesized in the laboratory. Wyoming bentonite (CG-50, CETCO), composed of sodium montmorillonite, was used as the base clay for the synthesis of these five organoclays. The natural organic content of the bentonite was 0.2%. The five QAC's used in the study were: (i) tetramethylammonium (TMA) chloride; (ii) tetraethylammonium (TEA) bromide; (iii) tetrabutylammonium (TBA) bromide; (iv) decyltrimethylammonium (DTMA) bromide; and (v) hexadecyltrimethylammonium (HDTMA) bromide.

Burns et al. [2006] performed various geotechnical tests on two organoclays synthesized in the laboratory. Wyoming bentonite (CG-50, American Colloid Co.) was used as the base clay for preparation of the organoclays. The two QAC's used in the study were: (i) benzyltriethylammonium (BTEA) chloride; and (ii) HDTMA bromide.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **46** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

Specific gravity tests performed by Bate [2010] and Bate et al. [2014] on the unmodified soil and the organoclays indicate that the specific gravity of the organoclays decreased with increasing organic carbon content and with increased percentage of cations exchanged, as shown in Figure B-2. The measured values of specific gravity shown in Figure B-2 were lower than those reported in Burns et al. [2006] (shown in Figure 3) but the trend is similar. Bate [2010] and Bate et al. [2014] indicate that the specific gravity of the organoclays at 25% total organic content to be 1.75. This result is consistent with the results of Lee et al. [2012] and Dovantzis [2009] as discussed earlier and presented in Table B-1.

Results of Atterberg limits of organoclays presented by Bate [2010] and Bate et al. [2014] indicate that, in general, the addition of the organic cation to bentonite decreases the liquid limit (LL) and increases the plastic limit (PL) when compared to the unmodified clay (i.e., Bentonite, LL = 274% and PL = 221%). Table B-2 summarizes the physical and mechanical properties of the tested organoclays. Figure B-4 presents the variation of LL and PL as a function of total organic content from Bate [2010]. Figure B-5 presents the variation of LL as a function of total organic content from Burns et al. [2006]. Results from these two figures indicate that the measured LL values from Bate [2010] are quite high (LL ~ 100% to 250%) when compared to Burns et al. [2006] (LL ~ 50% to 75%). Bate [2010] attributes this difference to the different base clay and the sample preparation methods. It is further pointed out that the soils in Burns et al. [2006] were oven dried before testing, whereas the soils in the Bate [2010] were not dehydrated before testing.

Bate [2010] and Bate et al. [2014] performed isotropic consolidated undrained (CU) triaxial shear tests on the organoclays. Figure 6 presents the results of the triaxial tests. Table B-3 presents the measured peak and critical state friction angles of the tested organoclays. The following observations were made by based on the test results:

- The tested organoclays exhibited a marked increase in frictional resistance when compared to the unmodified clay.
- The tested organoclays indicated peak shear strength indicative of structuring within the soil. While peak strengths are not common in reconstituted normally consolidated soils, it is encountered in organic soils. The peak shear strength was reached faster (i.e., at smaller strains) at low confining pressures than at high confining pressures.
- Increasing the total organic content of the clay soils resulted in an increased measured critical-state friction angle in the tested organoclays.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **47**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

- Increasing the cation loading through an increase in the quantity of organic carbon that was exchanged (i.e., increasing % CEC exchanged) with the clay resulted in an increased measured critical-state friction angle.

- As size on all branches of the quaternary ammonium cations was increased, the friction angle increased.

- As the length of a carbon chain was increased to 10 (DTMA), the friction angle increased; however, further increase of the carbon chain to 16 (HDTMA) resulted in a decrease in the frictional resistance.

Burns et al. [2006] measured the shear strength of the organoclays by performing strain controlled direct shear tests following ASTM D3080-90. The measured peak friction angles of BTEA and HDTMA clay showed divergent trends, with BTEA clay showing an increase in strength (20° to 38°), and HDTMA clay showing a decrease in strength (34° to 29°) as the total organic content increases from 50% to 100%. Figure B-7 presents the results obtained by Burns et al. [2006].

Reible [2005] performed unconsolidated undrained (UU) shear strength measurements on two organoclays (CETCO PM-200 and Aqua Technologies Inc. ET-1). Results from this study indicate that both organoclays showed significant reductions in strength after exposure to NAPL. However, Reible [2005] concludes that the two organoclays are expected to support the weight of an overlying column of sand (more than 50 ft tall at 100 psf unit weight) without failure if saturated with water or NAPL.

One-dimensional consolidation tests were performed by Burns et al. [2006] following ASTM D2435-96 to obtain the compressibility parameters of organoclays. The tests were performed at consolidation pressures of 10 pounds per square inch (psi), 15 psi and 25 psi. Figures B-8 and B-9 show the consolidation test results on the two organoclays. Results from the consolidation test indicate the following:

- Structure of the organic cation (i.e., HDTMA cation vs. BTEA cation) did not have a significant effect on the compression behavior of the HDTMA and BTEA organoclays.

- The presence of the organic phase on the clay surface altered the compressibility of the two organoclays. The compressibility of the organoclays decreased with increasing total organic content.

			HPH106A
Geosyntec▷	**Beech and Bonaparte**▷		Treatment Layer Design Evaluation
consultants	engineering p.c.		Revision 0
	an affiliate of Geosyntec Consultants		May 2017

Page **48** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**		Project No:	**HPH106A**

- The measured compression index (C_c) for the BTEA and HDTMA organoclays was 0.4 to 0.9, depending on the total organic content. The measured recompression index (C_r) for these organoclays was 0.05 to 0.1, depending on the organic content.
- The measured compression and recompression indices measured for the unmodified bentonite ($C_c = 5.8$; $C_r = 2.2$) is significantly larger than the values measured for the two organoclays investigated.

Lee et al. [2012] performed tests for the hydraulic conductivity to NAPL on three organoclays as a function of time. The three organoclays used in this study are presented in Table 1. In addition to the pure organoclays, sand-organoclays mixtures were also tested. Results from this study indicate that the hydraulic conductivity of organoclays to NAPL (permeant) decreases with time, with a rapid initial decrease followed by a gradual decrease that trends toward an equilibrium condition reflecting a progressive solvation of the organoclays. The researchers indicate that a true equilibrium condition was not achieved in their tests (i.e., hydraulic conductivity was still decreasing with time at the end of the test). Table B-4 presents these upper bound values on the long-term equilibrium hydraulic conductivity to NAPL. Figure B-10 presents the variation of hydraulic conductivity as a function of time. The researchers indicate that organic carbon content may be a good indicator of the hydraulic conductivity of organoclays to NAPL. Figure B-11 presents the measured hydraulic conductivity to NAPL as a function of the organic carbon content.

In summary, it was observed that the geotechnical properties of organoclays are highly dependent on the synthesized organoclays. Depending on the contaminant to be adsorbed, organoclays in permeable reactive barriers could be synthesized differently by using different cations (i.e., type of cation, cation size, cation length, etc.). Tests performed by Burns et al. [2006], Bate [2010], and Bate et al. [2014] indicate that the geotechnical properties of organoclays are highly dependent on their total organic carbon content. Depending on the selected organoclay for design, laboratory testing might be required to estimate the geotechnical properties of organoclays with a greater degree of confidence.

ORGANOCLAY REACTIVE CORE MAT (OC-RCM)

Introduction

Reactive core mat is a permeable composite mat consisting of reactive materials (typically organoclays or activated carbon) encapsulated in a non-woven core matrix bound between two

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **49**   of   **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**		Project No:	**HPH106A**

geotextiles. Depending on the type of OC-RCM, the top and bottom geosynthetic components may consist either of a woven geotextile, nonwoven geotextile, or combination thereof. A typical thickness of a reactive core mat is about 11 mm [Olsta, 2007].

Geotechnical Properties of OC-RCM

CETCO [2014b] performed direct shear tests on OC-RCM and silty-sand soil (unified soil classification system (USCS): SM). Direct shear strength results (large displacement) on the silty-sand compacted to 95% standard proctor density at optimum moisture content indicated a friction angle of 31° with cohesion of 30 psf. Direct shear tests were also performed on OC-RCM and silty-sand interfaces under soaked consolidated conditions. Figure B-12 presents the direct shear test results of the OC-RCM and silty-sand interface. Results from this figure indicate that the mean peak shear strength of an OC-RCM and silty-sand interface is approximately 30° with cohesion of 65 psf. The mean large displacement shear strength of the interface is approximately 26.5° and cohesion of 32.5 psf.

Since organoclay is used as the core for OC-RCM, the consolidation properties of OC-RCM's could be similar to that of organoclays.

GRANULAR ACTIVATED CARBON (GAC)

Introduction

Activated carbon is a form of carbon processed to have small, low-volume pores that increase the surface area available for adsorption or chemical reaction. Activated carbon is usually derived from carbonaceous material, including coal, peat, wood or nutshells (i.e., coconut). The manufacturing process consists of a two phases: (i) carbonization; and (ii) activation. The carbonization process involves drying and heading to separate by-products, including tars and other hydrocarbons, from the raw material as well as to drive off any gases generated. The carbonization process is completed by heating the material at 400-600°C in an oxygen-deficient atmosphere that cannot support combustion. The carbonized particles are "activated" by exposing them to an activating agent, such as steam at high temperature. The steam burns off the decomposition products from the carbonization phase to develop a porous, three-dimensional graphite lattice structure. The size of the pores developed during activation is a function of the time that they are exposed to the steam. Longer exposure times result in larger pore sizes [USACE, 2001].

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **50** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

Physical adsorption is the primary means by which activated carbon works to remove contaminants from liquids. Carbon's large surface area per unit weight allows the contaminants to adhere to the activated carbon media.

The large internal surface area of carbon has several attractive forces that work to attract other molecules. These forces manifest in a similar manner as gravitational force; therefore, contaminants in water are adsorbed (or adhered) to the surface of carbon from a solution as a result of differences in adsorbate concentration in the solution and in the carbon pores [TIGG, 2016a]. Physical adsorption occurs because all molecules exert attractive forces, especially molecules at the surface of a solid (i.e., pore walls of carbon), and these surface molecules seek to adhere to other molecules. The dissolved adsorbate migrates from the solution through the pore channels to reach the area where the strongest attractive forces are located. Contaminants adsorb because the attraction of the carbon surface for them is stronger than the attractive forces that keep them dissolved in solution. Contaminants that are organic, have high molecular weights, and are neutral, or non-polar, in their chemical nature are readily adsorbed on activated carbon.

Geotechnical properties of GAC

The solid, or skeletal, density of most activated carbons will range between 125-130 pcf. However, this would describe a material with essentially no surface area and no adsorptive capacity. For GAC, the apparent density (AD), or mass of a given volume of adsorbent particles is typically defined. This density will be significantly lower than the solid density, due to the presence of pores within particles, and void space between particles. In most commercial GACs, the AD variation is between 25-31 pcf [TIGG, 2016a].

The size of most GACs is given by the US Sieve range that will include the majority of the particles in a distribution of sizes. The particle size gradation of GAC varies depending on the project requirements. Liquid phase GAC have typical US sieve mesh sizes of 8×30, 12×20, 12×40 and 20×50 [TIGG, 2016b].

SAND + GAC MIXTURES

The geotechnical properties of sand could vary depending on, but not limited to, the particle size gradation and degree of compaction. Table B-5 presents the typical friction angles of soils based on the USCS classification [Geotechdata, 2013]. Sands, unlike clays, typically settle immediately after application of a load. For the same load, the settlement in sand is typically much smaller than that of normally consolidated clay. The settlement property of sands is often characterized by

		HPH106A
		Treatment Layer Design Evaluation
		Revision 0
		May 2017

Geosyntec▷

Beech and Bonaparte▷
engineering p.c.

consultants

an affiliate of Geosyntec Consultants

Page **51** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

Young's modulus. Table B-6 presents the typical values of Young's modulus for granular material [Geotechdata, 2013].

Budihardjo et al. [2015] investigated the shear strength of wet sand-GAC mixtures. The investigators performed four sets of direct shear tests on four different types of samples, consisting of pure sand and sand containing 5%, 10% and 15% carbon. The percentage carbon was calculated based on the dry weight of sand. Direct shear tests were performed at three confining pressures of 7.25 psi (50 kPa), 21.75 psi (150 kPa) and 36.25 psi (250 kPa). Results indicated that the shear strength of the sand-GAC mixtures decreased with increase in carbon content. The sand with no carbon, 5% carbon, 10% carbon and 15% carbon had friction angles of 34.3°, 29.0°, 28.6° and 27.6°, respectively.

Literature on the compressibility characteristics of sand-GAC mixtures could not be found. However, the compressibility of sand-GAC mixtures is likely dominated primarily by elastic settlement.

COMPRESSIBILITY OF ORGANOCLAYS

Basic calculations for the compressibility of organoclays were performed to calculate theoretical possible settlement of the organoclay when subjected to different vertical loads. The loading on the organoclay is expected from the various cap layers above it. Given the uncertainty in the final cover system layer component thickness and unit weights, the calculations were performed over a range of values for vertical loading. For these analyses, it is assumed that the organoclay layer is completely submerged with a total unit weight of 109 pcf.

From Figures B-8 and B-9 [Burns et al., 2006] it is observed that the maximum and minimum compression indices (C_c) for the two tested organoclays were 0.9 and 0.4 respectively. The corresponding void ratios of for these two tests are 2.1 and 1.5 respectively. Based on these values, the maximum and minimum modified compression index (C_{ce}) can be estimated as 0.29 and 0.16 respectively.

Based on these input parameters, primary consolidation settlement calculations of an organoclay layer subjected to different vertical loads were performed, and results are presented in Figures B-13, B-14, and B-15 for organoclay thicknesses of 0.5-ft, 1-ft, and 1.5-ft, respectively.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **52** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

References

Bate, B. (2010). "Engineering Behavior of Fine-Grained Soils Modified With a Controlled Organic Phase." PhD Thesis, Georgia Institute of Technology.

Bate, B., Zhao, Q., and Burns, S. (2014). "Impact of Organic Coatings on Frictional Strength of Organically Modified Clay." *J. Geotech. Geoenviron. Eng.*, Vol. 140, Issue 1.

Benson, C., Jo, H., and Musso, T. (2014). "Hydraulic Conductivity of Organoclay and Organoclay-Sand Mixtures to Fuels and Organic Liquids." *J. Geotech. Geoenviron. Eng.*, Vol. 141, Issue 2.

Budihardjo, M.A., Chegenizadeh, A., Nikraz, H. (2015). "Investigation of the Strength of Carbon-Sand Mixtures." The 7th World Congress in Particle Technology (WCPT7), Pocedia Engineering 102, 634-639.

Burns, S., Bartelt-Hunt, S., Smith, J., and Redding, A. (2006). "Coupled Mechanical and Chemical Behavior of Bentonite Engineered with a Controlled Organic Phase." *J. Geotech. Geoenviron. Eng.*, Vol. 132, Issue 11.

CETCO (2014a). "Technical Reference: Permeability and Particle Size Testing of Organoclay PM-199."

CETCO (2014b). "Technical Reference: RCM® Direct Shear Test Data."

Dovantzis, Kostas. (2009). "Evaluation of Organoclay Permeable Adsorptive Barrier to Manage DNAPL and Dissolved PAHs in Groundwater Seepage." 16th International Petroleum and Biofuels Environmental Conference, Houston, TX.

Geotechdata (2013), Angle of Friction, http://geotechdata.info/parameter/angleoffriction.html (as of September 14.12.2013).

Lagaly, G. (1984), Clay-organic reactions, Interaction, *Phil. Trans. R. Soc. London*, A-311:315-332.

Lee, S., Ören, A. H., Benson, C. H., and Dovantzis, K. (2012). "Organoclays as variably permeable reactive barrier media to manage NAPLs in ground water." J. Geotech. Geoenviron. Eng., Vol. 138, Issue 2, 115–127.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **53**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Lo, I. M. C., and Yang, X. (2001). "Laboratory investigation of the migration of hydrocarbons in organobentonite." Environ. Sci. Technol., 35(3), 620-625.

Lorenzetti, R. J., Bartelt-Hunt, S. L., Burns, S. E., and Smith, J. A. (2005). "Hydraulic conductivities and effective diffusion coefficients of geosynthetic clay liners with organobentonite amendments." Geotextile Geomembr., 23(5), 385–400.

Mortland, M. M., Shaobai, S., and Boyd, S. A. (1986), Clay-organic complexes as adsorbants for phenols and chlorophenols: clays & clay minerals, 34(5):581-585.

Olsta, J.T. (2007). "Installation of an In-Situ Cap at a Superfund Site." Proceedings of the Fourth International Conference on Remediation of Contaminated Sediments, Savannah, Georgia.

Reible, D. D. (2005). "Organoclay Laboratory Study: McCormick & Baxter", University of Texas at Austin. Oregon Department of Environmental Quality Project 005-05, 36 pp, Sep 2005.

Smith, J. A., Bartelt-Hunt, S. L., and Burns, S. E. (2003). "Sorption and permeability of gasoline hydrocarbons in organobentonite porous media." J. Hazard. Mater., 96(1), 91–97.

TIGG (2016a). "Activated Carbon, Properties of GAC". Retrieved on September 12, 2016 from http://www.tigg.com/library.html

TIGG (2016b). "Granular Activated Carbon (GAC) Selection". Retrieved on September 30, 2016 from http://www.tigg.com/granular-activated-carbon.html

United States Army Corps of Engineers (USACE) (2001). "Engineering and Design, Adsorption Design Guide." Design Guide No. 1110-1-2.

United States Environmental Protection Agency (EPA) (2013). "Record of Decision, Gowanus Canal Superfund Site, Brooklyn, King County, New York", September 2013.

| CP: | DM | Date: | 5/18/2017 | APC: | JAW | Date: | 5/19/2017 | CC: | JAW | Date: | 5/19/2017 |

Client: RD Group   Project: Gowanus Canal Superfund Site   Project No: HPH106A

TABLES

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Table B-1. Physical Properties of Organoclays
[Dovantzis, 2009 and Lee at al., 2012]

Organoclay	Specific Gravity, G_s	Organic Content (%)	Hydraulic Conductivity to Water (cm/s)
OC-1 (PM-199)	1.75	25.00	0.14
OC-2 (ET-1)	2.00	15.50	0.12
OC-3 (EC-199)	1.75	26.90	0.39

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **56** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

Table B-2. Physical and Mechanical Properties of Tested Organoclays
[Bate, 2010 and Bate et al., 2014]

Organic Cation of Organoclay	CEC[1] Exchanged (%)	LL/PI (%)	Specific Gravity	Water Content [2] (%)
TMA	30	-	-	164
	60	-	-	162
	100	266/184	2.80	184
TEA	100	140/74	2.23	156
TBA	100	118/46	2.20	136
DTMA	100	205/98	2.26	228
HDTMA	100	219/130	1.75	148

Notes:
1. CEC – Cation Exchange Capacity.
2. This is the water content of the slurried organoclays (i.e., no consolidation stress was applied).

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **57**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Table B-3. Measured Critical-State (CS) Friction Angles of Organoclays
[Bate, 2010 and Bate et al., 2014]

Organic Cation of Organoclay	CEC Exchanged (%)	Water Content (%)			ϕ'_{peak}[1] / Cohesion in kPa	ϕ'_{cs}[1] / Cohesion in kPa	ϕ'_{cs}[2]
		50 kPa	100 kPa	200 kPa			
TMA	30	144	121	105	31.5°/21.06	26.3°/27.27	34.0°
	60	141	122	101	34.8°/18.85	33.9°/17.08	38.5
	100	172	152	126	44.0°/18.91	30.4°/30.02	41.1
TEA	100	136	120	92	59.0°/8.95	40.7°/16.75	46.7
TBA	100	131	107	82	49.6°/16.48	41.1°/19.29	48.4
DTMA	100	206	190	146	59.2°/29.96	44.8°/21.15	52.6
HDTMA	100	147	116	99	81.9°/3.50	53.5°/16.83	60.8

Notes:
1. These values are the best fit lines of the data presented in Bate [2010].
2. These values are the best fit lines assuming a zero cohesion [Bate et al, 2014].

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | | Project No: | **HPH106A** |

Table B-4. Summary of Hydraulic Conductivities to NAPL and Water for Organoclays and Organoclay-Sand Mixtures [Lee et al., 2012]

Material	Permeant liquid	Test duration (days)	Hydraulic conductivity (m/s)
OC-1	NAPL/Water	75	7.6×10^{-12} (NAPL) 9.6×10^{-12} (water)
OC-2	NAPL	46	3.4×10^{-11}
OC-3	NAPL/Water	75	3.7×10^{-12} (NAPL) 1.1×10^{-11} (water)
0% OC-1	NAPL	1	4.1×10^{-7}
10% OC-1	NAPL	1	2.6×10^{-8}
25% OC-1	NAPL	42	8.6×10^{-11}
50% OC-1	NAPL	42	2.8×10^{-12}

Notes:
1. All organoclays-sand mixtures were prepared with OC-1 organoclay.
2. Percent shown in material column is organoclay fraction.

Tests with permeant liquid marked as NAPL/water were first permeated with NAPL and then by water.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **59** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Table B-5. Typical Values of Soil Friction Angles for Different Soils According to USCS Classification [Geotechdata, 2013]

Description	USCS	Soil friction angle (°)		
		Minimum	Maximum	Specific value
Well graded gravel, sandy gravel, with little or no fines	GW	33	40	
Poorly graded gravel, sandy gravel, with little or no fines	GP	32	44	
Sandy gravels - Loose	(GW, GP)			35
Sandy gravels - Dense	(GW, GP)			50
Silty gravels, silty sandy gravels	GM	30	40	
Clayey gravels, clayey sandy gravels	GC	28	35	
Well graded sands, gravelly sands, with little or no fines	SW	33	43	
Well-graded clean sand, gravelly sands - Compacted	SW	-	-	38
Well-graded sand, angular grains - Loose	(SW)			33
Well-graded sand, angular grains - Dense	(SW)			45
Poorly graded sands, gravelly sands, with little or no fines	SP	30	39	
Poorly-graded clean sand - Compacted	SP	-	-	37
Uniform sand, round grains - Loose	(SP)			27
Uniform sand, round grains - Dense	(SP)			34
Sand	SW, SP	37	38	
Loose sand	(SW, SP)	29	30	
Medium sand	(SW, SP)	30	36	
Dense sand	(SW, SP)	36	41	
Silty sands	SM	32	35	
Silty clays, sand-silt mix - Compacted	SM	-	-	34
Silty sand - Loose	SM	27	33	
Silty sand - Dense	SM	30	34	

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: __DM__   Date: __5/18/2017__   APC: __JAW__   Date: __5/19/2017__   CC: __JAW__   Date: __5/19/2017__

Client: __RD Group__   Project: __Gowanus Canal Superfund Site__   Project No: __HPH106A__

Description	USCS	Soil friction angle (°)		
		Minimum	Maximum	Specific value
Clayey sands	SC	30	40	
Calyey sands, sandy-clay mix - compacted	SC			31
Loamy sand, sandy clay Loam	SM, SC	31	34	
Inorganic silts, silty or clayey fine sands, with slight plasticity	ML	27	41	
Inorganic silt - Loose	ML	27	30	
Inorganic silt - Dense	ML	30	35	
Inorganic clays, silty clays, sandy clays of low plasticity	CL	27	35	
Clays of low plasticity - compacted	CL			28
Organic silts and organic silty clays of low plasticity	OL	22	32	
Inorganic silts of high plasticity	MH	23	33	
Clayey silts - compacted	MH			25
Silts and clayey silts - compacted	ML			32
Inorganic clays of high plasticity	CH	17	31	
Clays of high plasticity - compacted	CH			19
Organic clays of high plasticity	OH	17	35	
Loam	ML, OL, MH, OH	28	32	
Silt Loam	ML, OL, MH, OH	25	32	
Clay Loam, Silty Clay Loam	ML, OL, CL, MH, OH, CH	18	32	
Silty clay	OL, CL, OH, CH	18	32	
Clay	CL, CH, OH, OL	18	28	
Peat and other highly organic soils	Pt	0	10	

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **61**   of   **101**
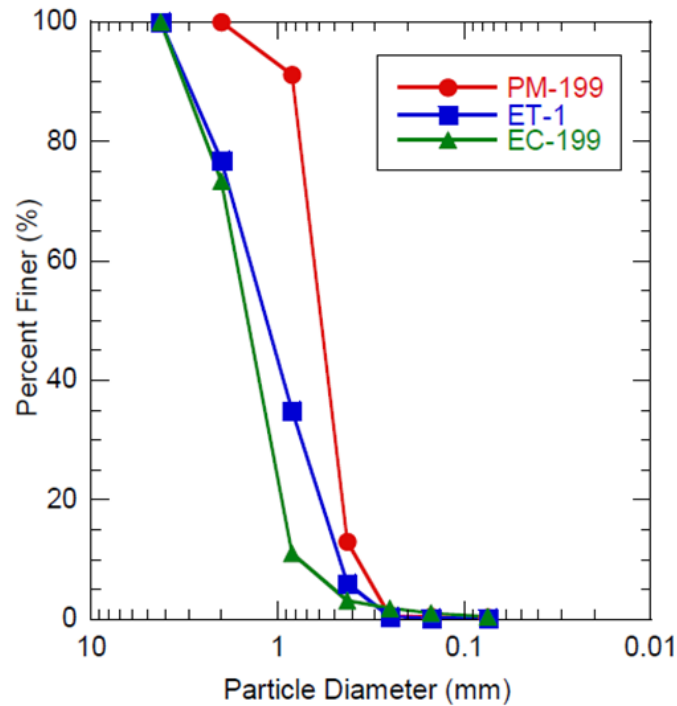
CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Table B-6. Typical Young's Modulus for Granular Material
[Geotechdata, 2013]

USCS	Description	Young's Modulus (mega pascals, MPa)		
		Loose	Medium	Dense
GW, SW	Gravels/Sand well-graded	30-80	80-160	160-320
SP	Sand, uniform	10-30	30-50	50-80
GM, SM	Sand/Gravel silty	7-12	12-20	20-30

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **62** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

FIGURES

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

Page **63** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

(a)
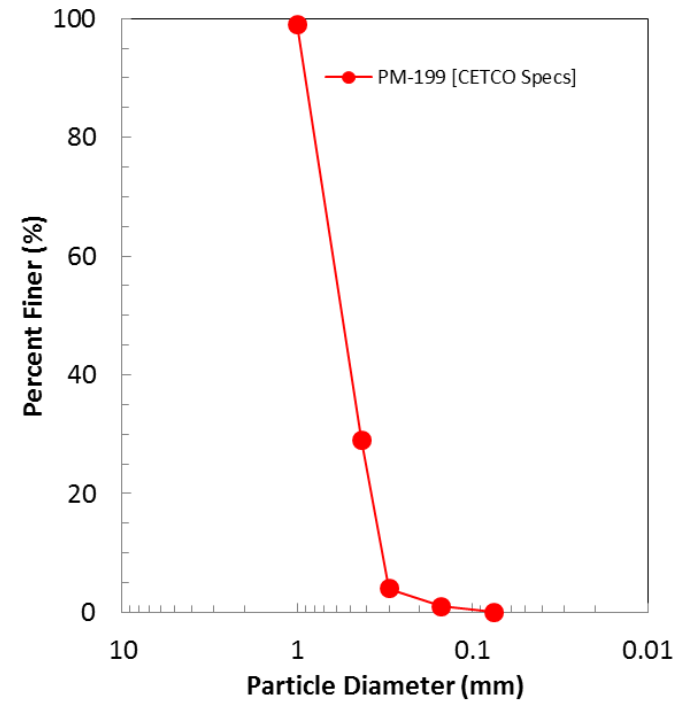
(b)

Figure B-1. Grain Size Distribution (GSD) of Commercially Available Organoclays: (a) Measured GSD Using Mechanical Sieving following ASTM D422 [Dovantzis, 2009 and Lee at al., 2012]; and (b) Reported GSD from CETCO Technical Specifications [CETCO, 2014a]

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page	**64**	of	**101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**
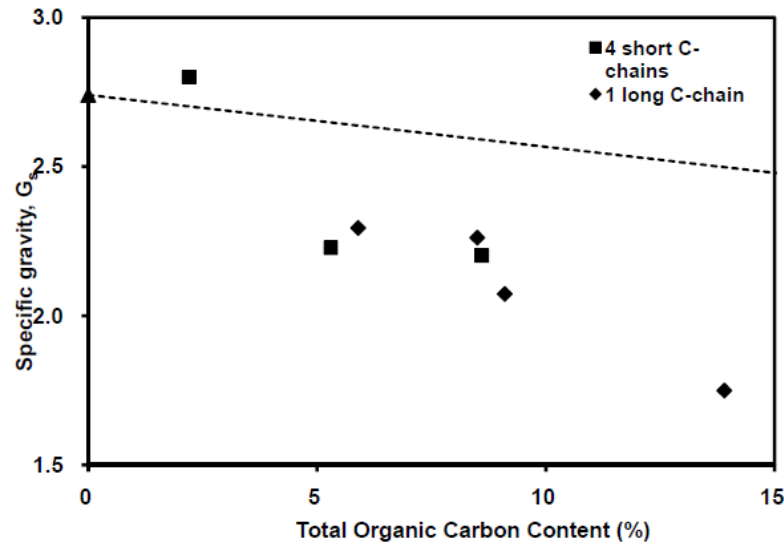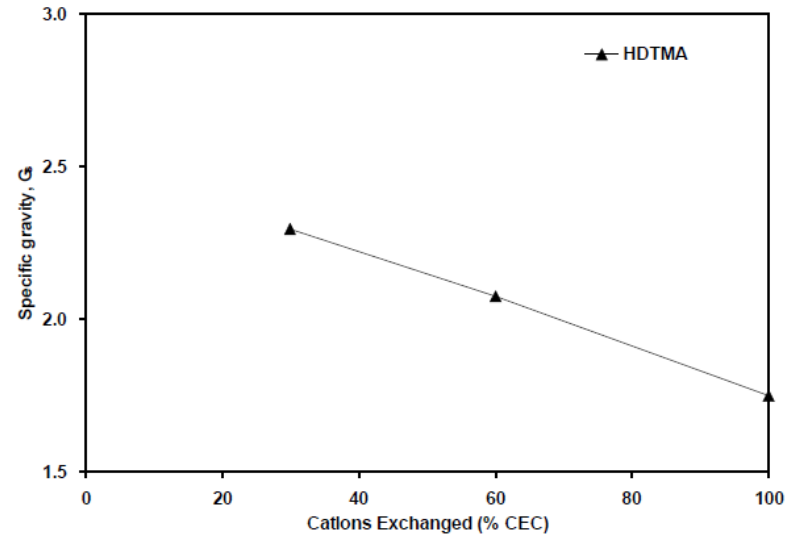
(a)   (b)

Figure B-2. Specific Gravity of Organobentonites [Bate, 2010]: (a) As a Function of Total Organic Content (dashed line indicates theoretical calculation assuming a linear variation); and (b) at Increasing Percentages of Cation Exchange Capacity

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
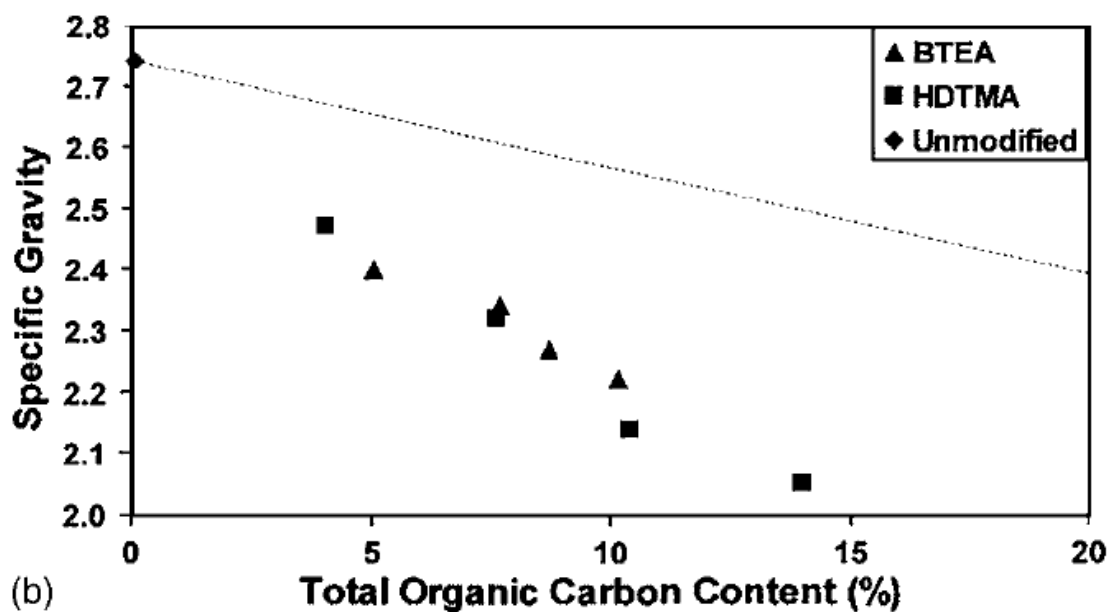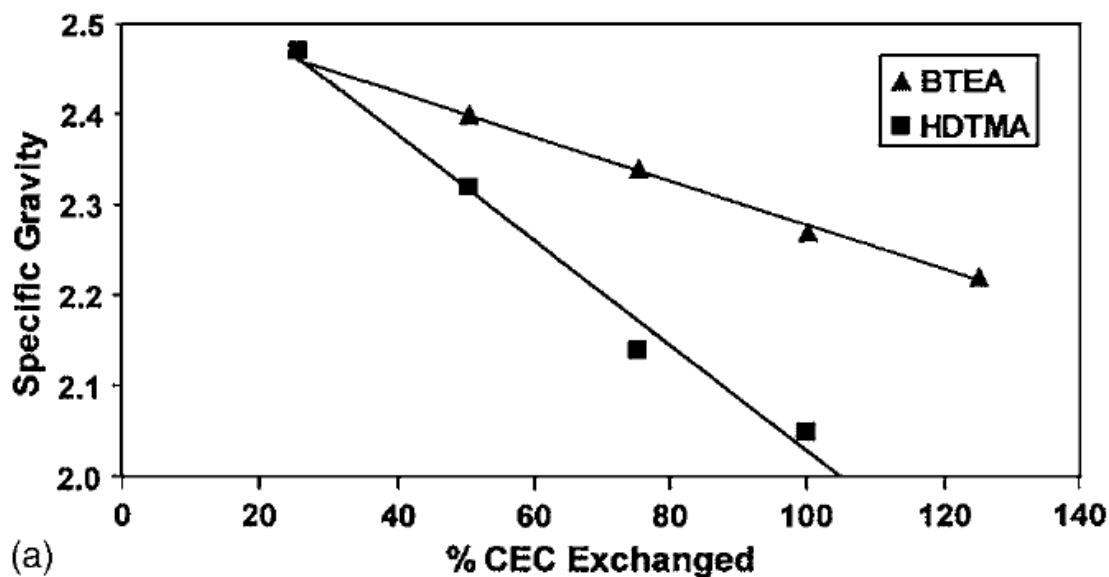
Figure B-3. Specific Gravity of Organobentonites [Burns et al., 2006]: (a) As a Function of % CEC); and (b) As a Function of Total Organic Carbon Content

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
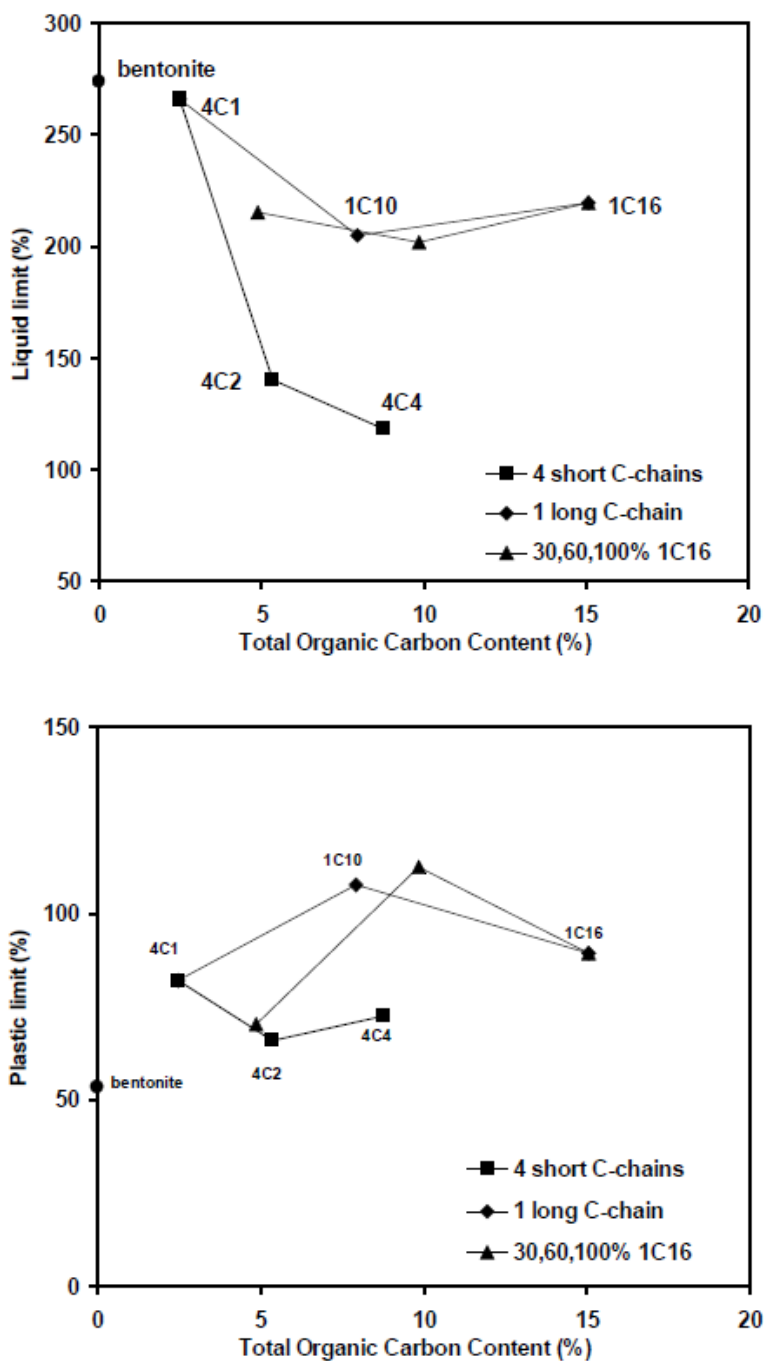
Figure B-4. Atterberg Limits as a Function of Total Organic Carbon Content [Bate, 2010]: (a) Liquid Limit; and (b) Plastic Limit

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **67**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
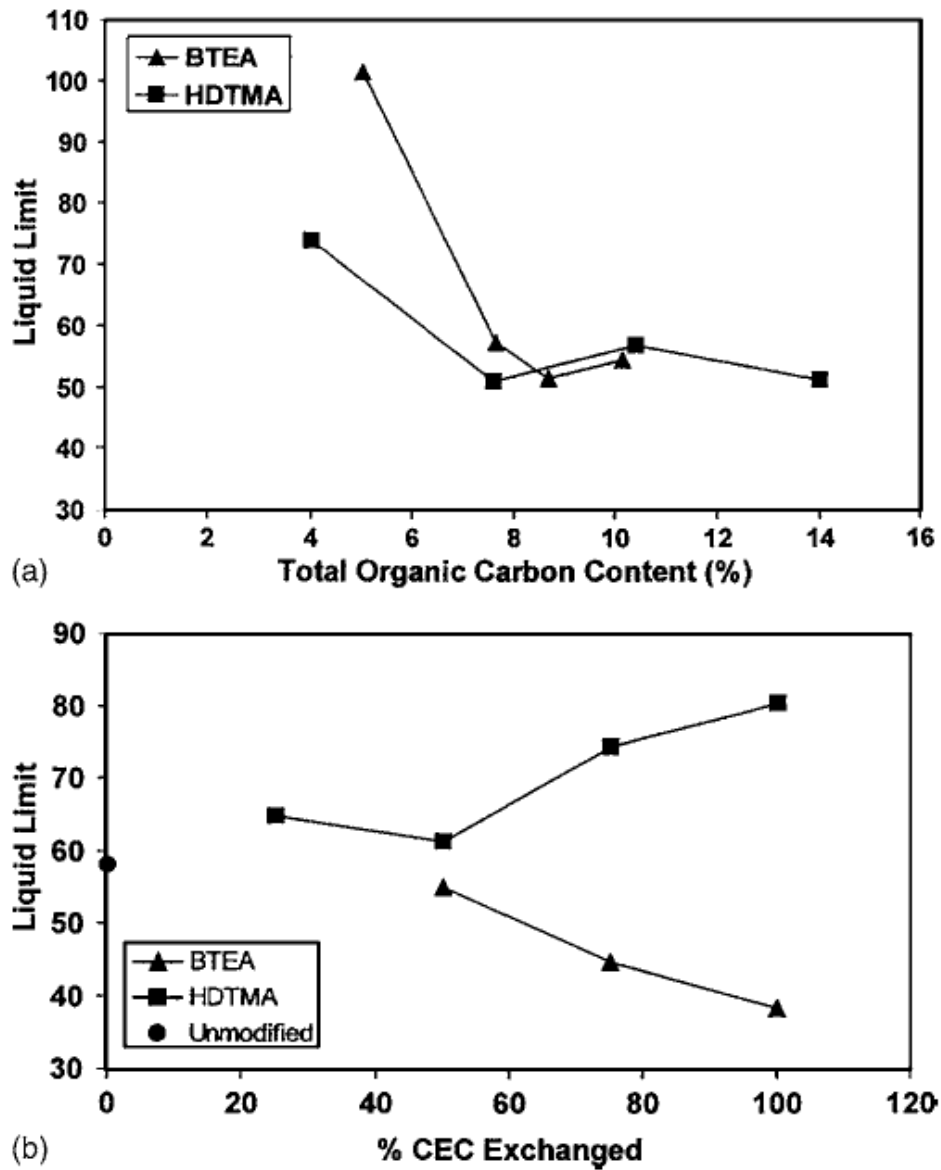
Figure B-5. Liquid Limit of the Organoclays as Function of Total Organic Content [Burns et al., 2006]: (a) in Water; and (b) in Methanol

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
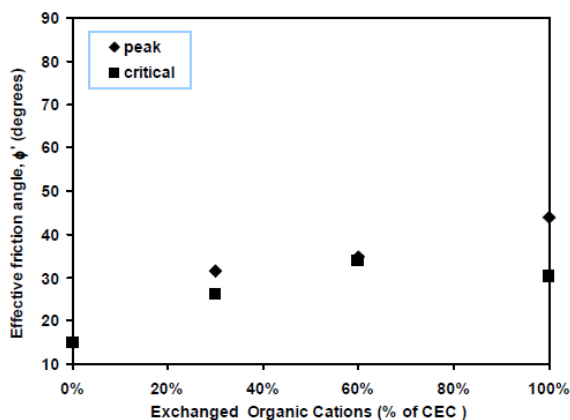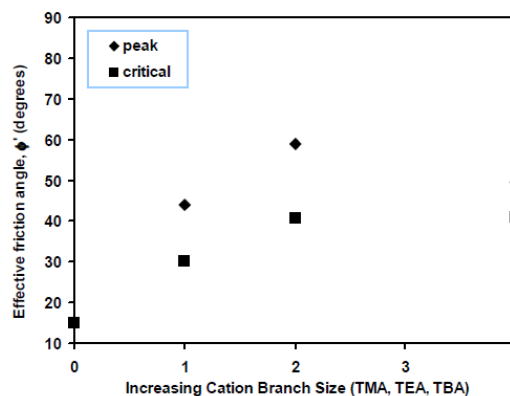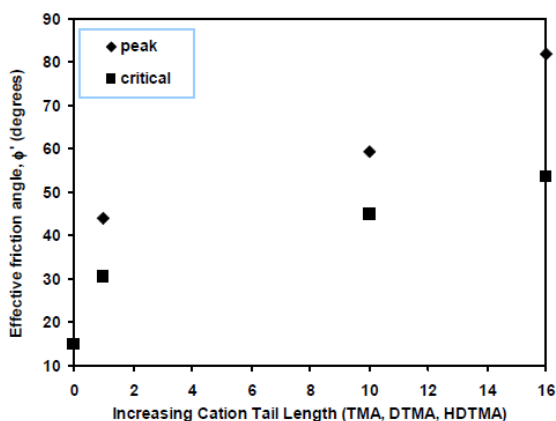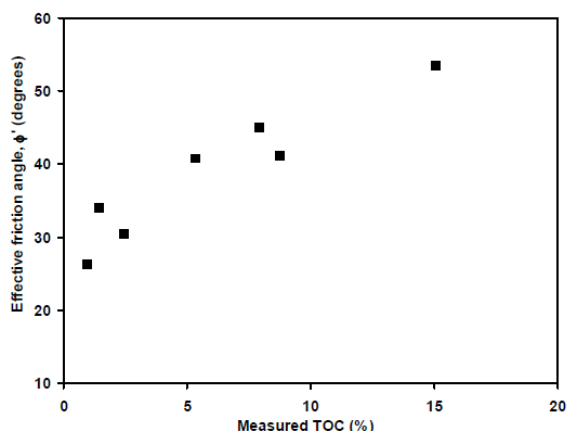
Figure B-6. Peak and Critical State Friction Angles of Tested Organoclays [Bate, 2010]: (a) as a Function of Increased Density of Organic Coating on the Clay; (b) as a Function of Increasing Branch Size; (c) as a Function of Increased Tail Length of the Organic Cation; and (d) as a Function of Total Organic Content

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
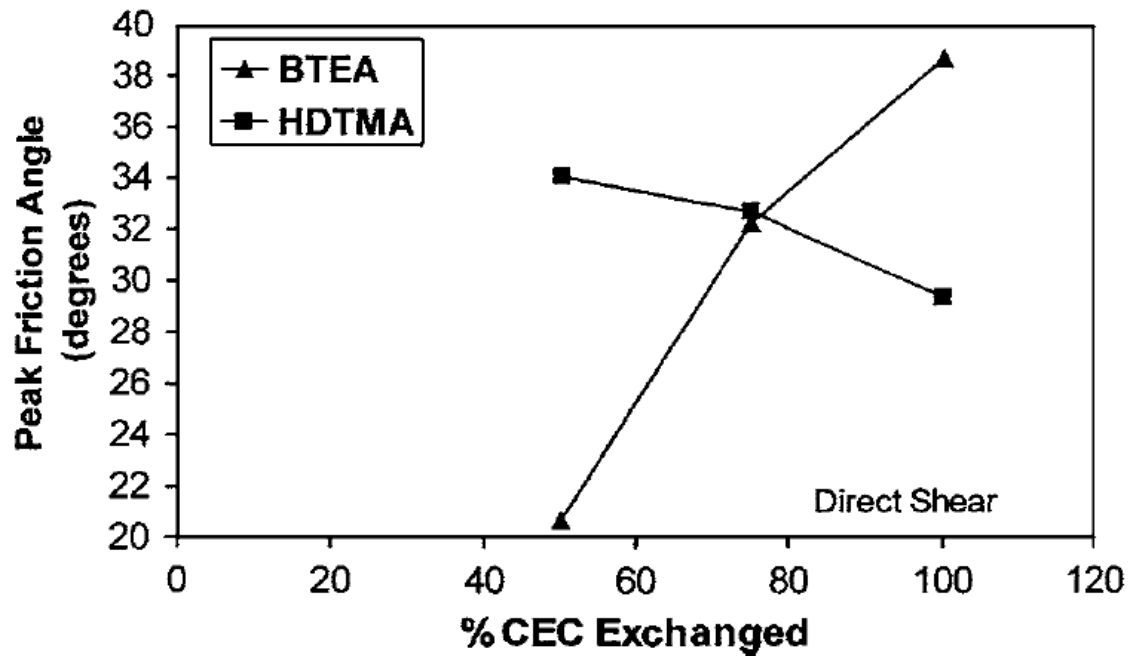
Figure B-7. Measured Peak Friction Angle from Direct Shear Testing [Burns et al., 2006]

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **70**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
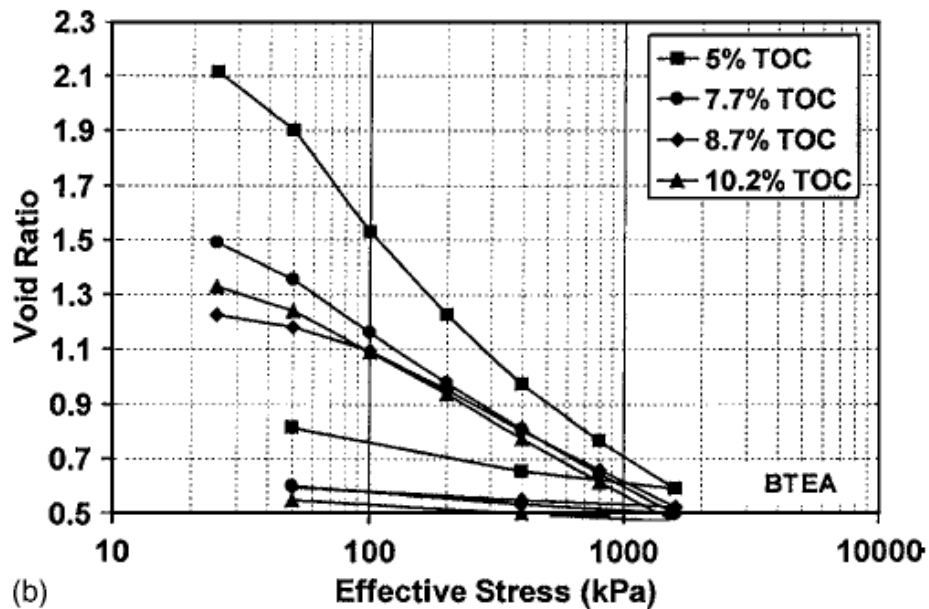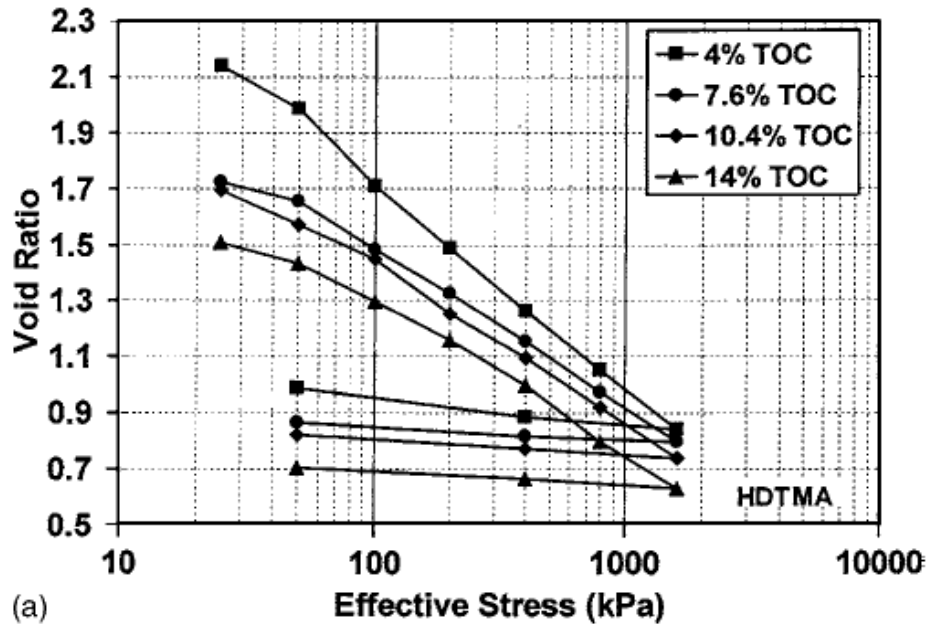
Figure B-8. Consolidation Test Results [Burns et al., 2006]:
(a) HDTMA organoclays; and (b) BTEA clay

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **71**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
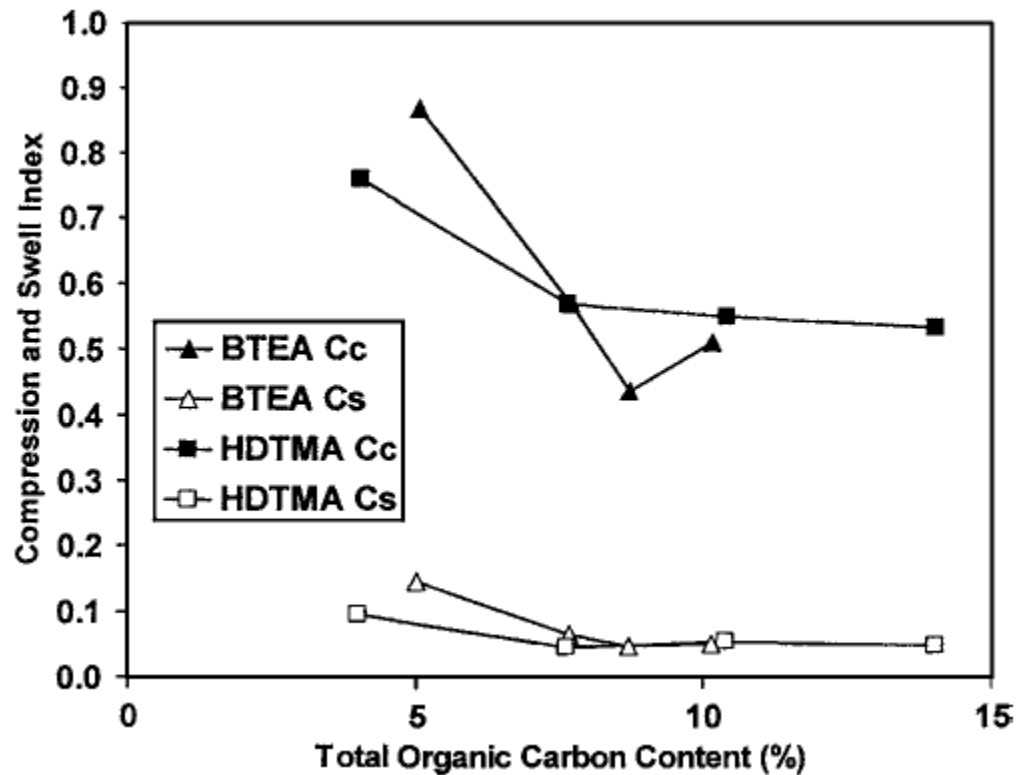
Figure B-9. Compression and Recompression Indices of Organoclays as Function of Total Organic Carbon Content [Burns et al., 2006]

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

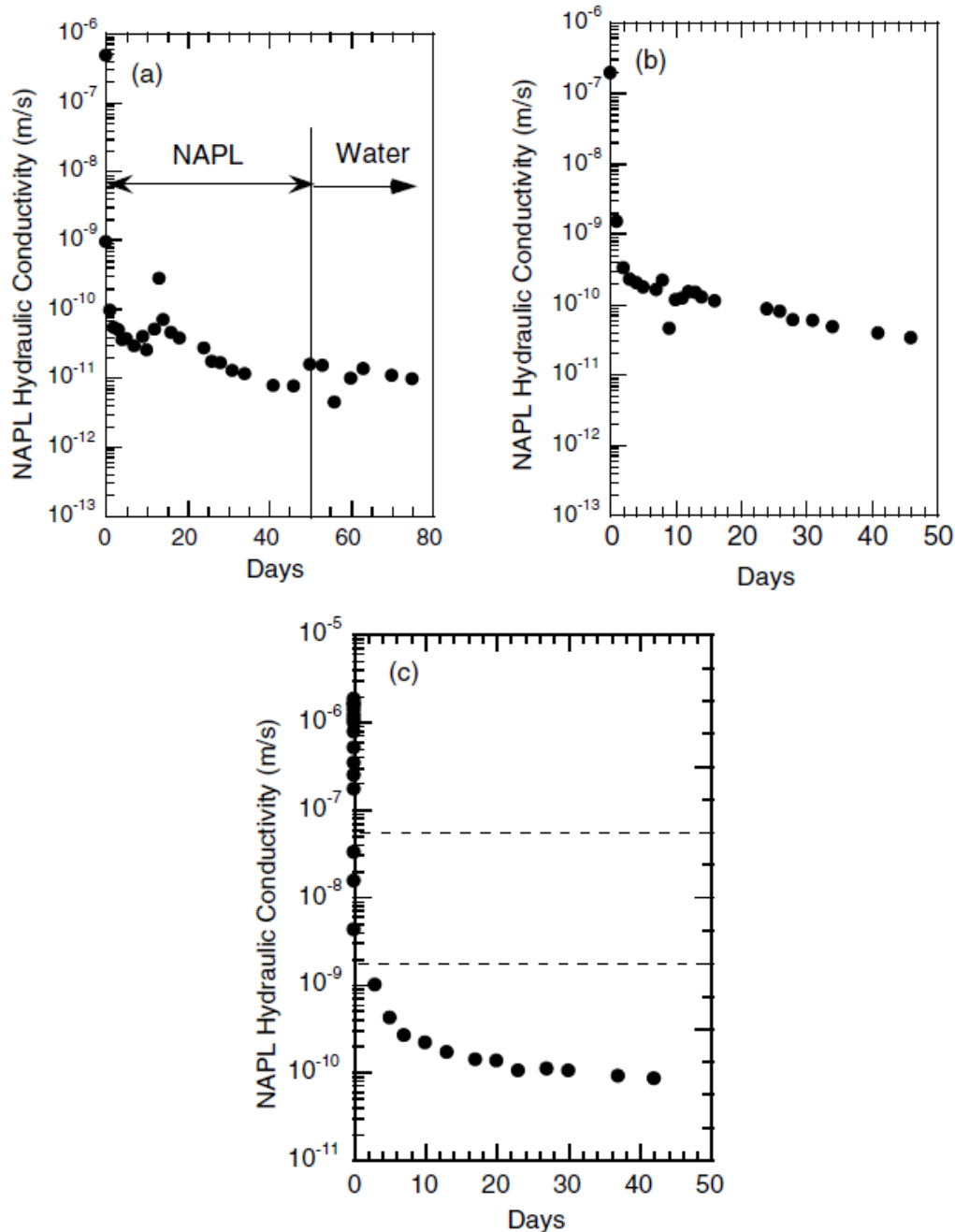| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

Figure B-10. Hydraulic Conductivity to NAPL [Lee et al., 2012] for: (a) Organoclay OC-1; (b) Organoclay OC-2; and (c) 25% OC-1 and Sand Mixture (by Weight)

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

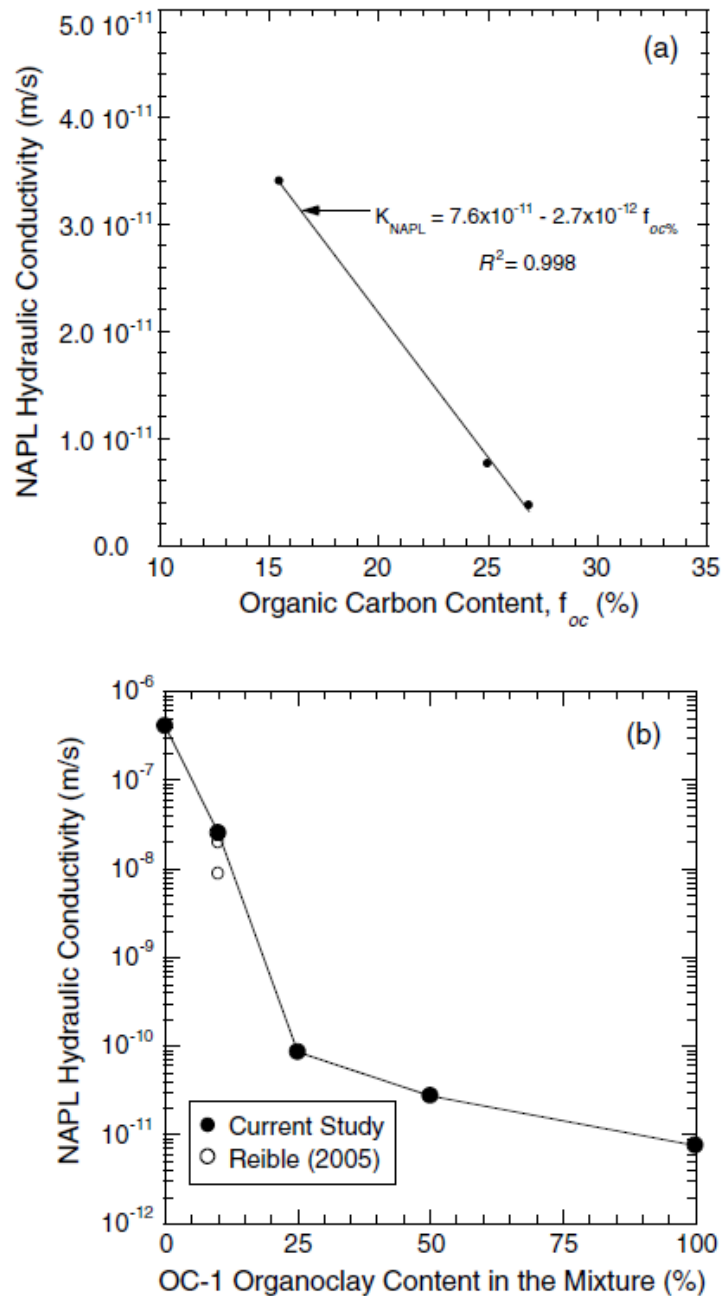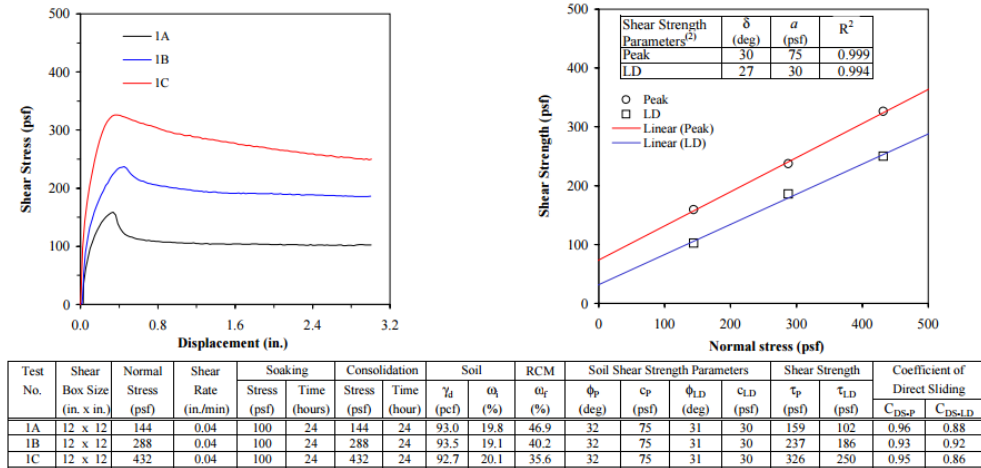| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

Figure B-11. Hydraulic Conductivity to NAPL [Lee et al., 2012]: (a) Organoclays as a Function of Organic Carbon Content; and (b) Organoclay-Sand Mixtures as a Function of Organoclay Content
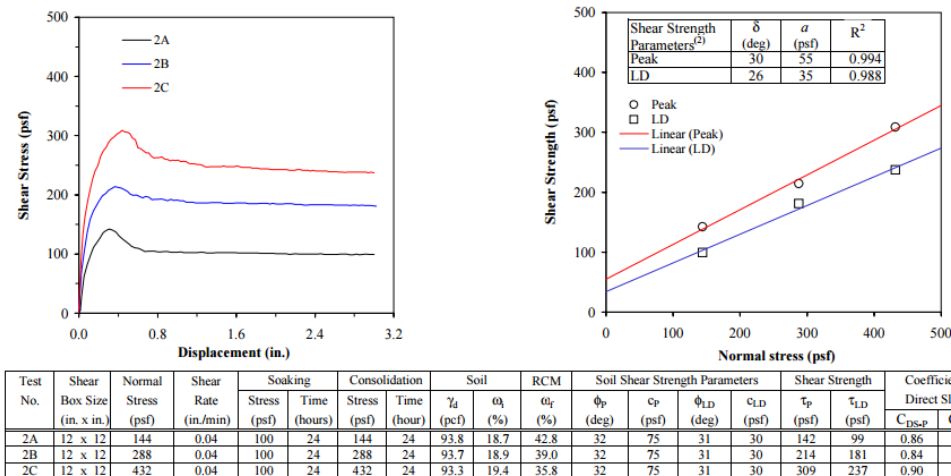
Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

Shear Strength Parameters[2]	δ (deg)	a (psf)	R²
Peak	30	75	0.999
LD	27	30	0.994

Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hours)	Consolidation Stress (psf)	Consolidation Time (hour)	Soil γd (pcf)	Soil ωi (%)	RCM ωf (%)	Soil Shear Strength Parameters φP (deg)	cP (psf)	φLD (deg)	cLD (psf)	Shear Strength τP (psf)	τLD (psf)	Coefficient of Direct Sliding CDS-P	CDS-LD
1A	12 x 12	144	0.04	100	24	144	24	93.0	19.8	46.9	32	75	31	30	159	102	0.96	0.88
1B	12 x 12	288	0.04	100	24	288	24	93.5	19.1	40.2	32	75	31	30	237	186	0.93	0.92
1C	12 x 12	432	0.04	100	24	432	24	92.7	20.1	35.6	32	75	31	30	326	250	0.95	0.86

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the silty sand-and back side of RCM in each test.
(2) The reported total-stress parameters of friction angle and cohesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

(a)

Shear Strength Parameters[2]	δ (deg)	a (psf)	R²
Peak	30	55	0.994
LD	26	35	0.988

Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hours)	Consolidation Stress (psf)	Consolidation Time (hour)	Soil γd (pcf)	Soil ωi (%)	RCM ωf (%)	Soil Shear Strength Parameters φP (deg)	cP (psf)	φLD (deg)	cLD (psf)	Shear Strength τP (psf)	τLD (psf)	Coefficient of Direct Sliding CDS-P	CDS-LD
2A	12 x 12	144	0.04	100	24	144	24	93.8	18.7	42.8	32	75	31	30	142	99	0.86	0.85
2B	12 x 12	288	0.04	100	24	288	24	93.7	18.9	39.0	32	75	31	30	214	181	0.84	0.89
2C	12 x 12	432	0.04	100	24	432	24	93.3	19.4	35.8	32	75	31	30	309	237	0.90	0.82

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the silty sand-and back side of RCM in each test.
(2) The reported total-stress parameters of friction angle and cohesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

(b)

Figure B-12. Direct Shear Testing Results of Silty-sand and OC-RCM Interfaces [CETCO, 2014b]

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **75** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

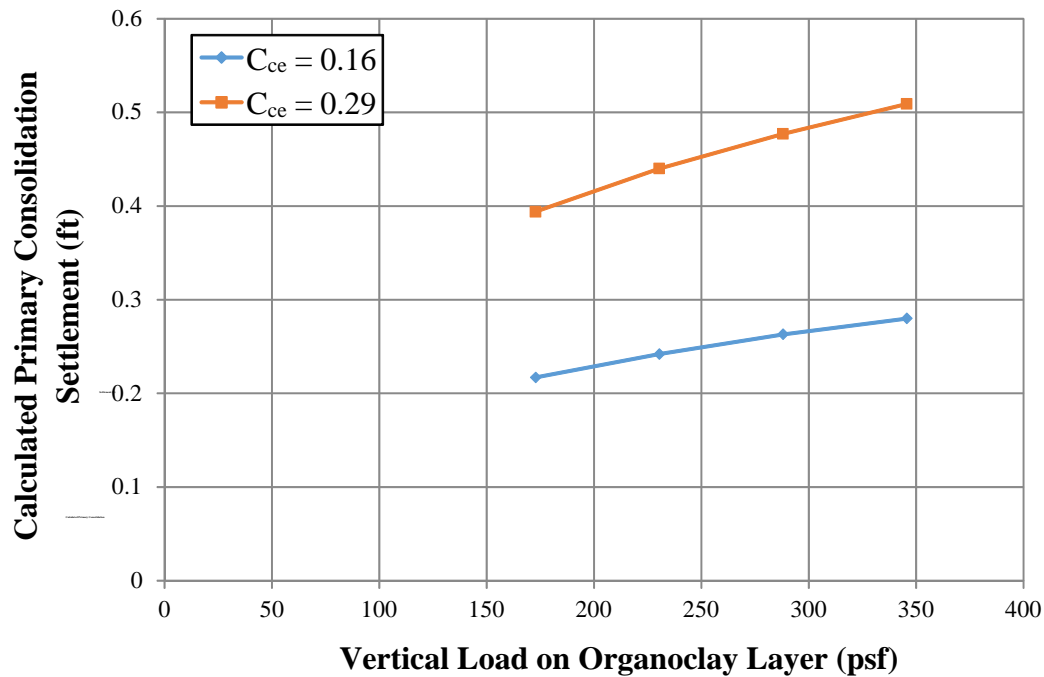| Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**		Project No:	**HPH106A**
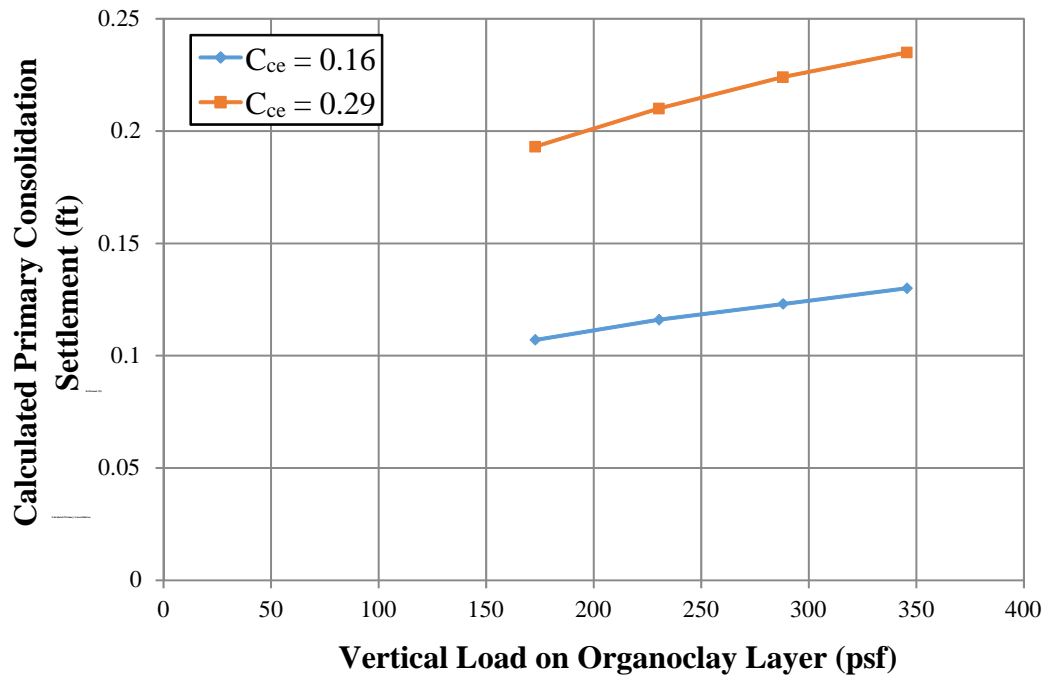
Figure B-13. Calculated Primary Consolidation Settlement of 0.5-ft Thick Organoclay Submerged in Water and Subjected to Different Vertical Loads

Notes:
1. C_{ce} of 0.16 is the minimum calculated modified compressive index of the organoclays from Burns et al. [2006].
2. C_{ce} of 0.29 is the maximum calculated modified compressive index of the organoclays from Burns et al. [2006].

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
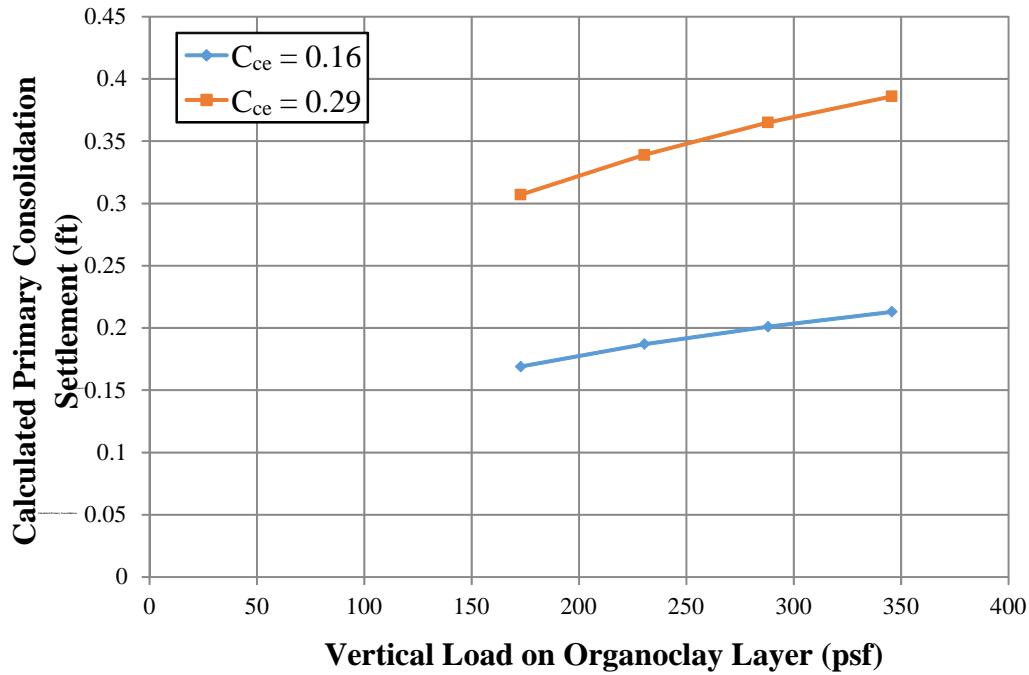
Figure B-14. Calculated Primary Consolidation Settlement of 1-ft Thick Organoclay Submerged in Water and Subjected to Different Vertical Loads

Notes:
1. C_{ce} of 0.16 is the minimum calculated modified compressive index of the organoclays from Burns et al. [2006].
2. C_{ce} of 0.29 is the maximum calculated modified compressive index of the organoclays from Burns et al. [2006].

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **77**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Figure B-15. Calculated Primary Consolidation Settlement of 1.5-ft Thick Organoclay Submerged in Water and Subjected to Different Vertical Loads

Notes:

1. Cce of 0.16 is the minimum calculated modified compressive index of the organoclays from Burns et al. [2006]. Cce of 0.29 is the maximum calculated modified compressive index of the organoclays from Burns et al. [2006].

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

ATTACHMENT C POTENTIAL FOR CONSOLIDATION-INDUCED DNAPL EXPRESSION

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **79**   of   **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

INTRODUCTION

The Gowanus Canal Superfund Site (Site), is a tidally influenced waterbody in Brooklyn, New York consisting of a 1.8-mile Canal and associated turning basins (herein referred to collectively as the Canal). The selected remedy in the 2013 Record of Decision (ROD) for the Site (EPA, 2013) includes, in part, dredging the entire layer of soft sediment, in situ stabilization (ISS) in select areas, and construction of a multilayered cap to isolate and prevent the migration of dense non-aqueous phase liquid (DNAPL) and polycyclic aromatic hydrocarbon (PAH)-impacted pore water from the newly exposed native sediments. The general cap configuration as described in the ROD consists of an armor layer, an isolation layer and an active treatment layer. The ROD described the treatment layer (1 foot [ft] in Remediation Treatment Area 1 (RTA1) and RTA2, and 0.5 ft in RTA3) as conceptually consisting of an oleophilic clay-sand mixture, with the exact configuration to be determined during the remedial design.

Placement of cap layers may result in generation of excess pore pressures in the underlying native alluvial sediments. The dissipation of this excess pore pressure, or consolidation, is achieved by the flow of pore fluids from the area subject to excess pore pressure (i.e., sediment below the cap). This consolidation water will likely flow both upwards into the cap and downwards into the sandy glacial deposits below. In addition to pore water, DNAPL may be present in the voids or pores between the soil particles. As a result, DNAPL could be mobilized together with the pore water flow, potentially resulting in transient DNAPL migration into the cap.

This document presents the results of a literature review conducted to evaluate the likelihood of DNAPL mobilization from native sediment pore spaces upon loading and consolidation (primary and secondary) due to the cap placement. The objective of this review is to outline the consolidation mechanism that will occur when the cap is placed and understand the conditions and time frame under which DNAPL expression may be possible as a result of consolidation.

SETTLEMENT AND CONSOLIDATION OF SOILS

Introduction

Soil is composed of a matrix of solid particles with fluids (e.g., water, air, contaminants, etc.) in the voids within the matrix. In saturated soil, such as the bed sediments beneath the Gowanus Canal, these fluids within the matrix consist of aqueous phase liquids (i.e. water and solutes) and/or

Geosyntec▷ consultants	Beech and Bonaparte▷ engineering p.c. *an affiliate of Geosyntec Consultants*	

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

non-aqueous phase liquids (NAPL). A soil matrix in equilibrium with aqueous and non-aqueous phases contains a stable proportion of fluid to solid particles. The ratio of the volume of the voids (i.e., fluids) to the volume of the solids is called the void ratio, *e*. Dense sands and stiff clays tend to have a low void ratio of 0.3 to 0.6, while soft clays and sediments tend to have void ratios higher than 1, up to void ratios of 2 to 3 in soft organic clays. The ratio of the volume of the voids (i.e., fluids) to the total volume of the solids and fluids is called the porosity, *n*. The ratio of the weight of the water to the weight of the solid particles is called the moisture content, *w*. Dense sands and stiff clays tend to have a low moisture content of 15 to 20 percent, while soft clays and sediments tend to have moisture contents higher than 30 percent, up to moisture contents of 120 percent or higher in soft organic clays. When a soil is subjected to a shear or normal stress, these void ratios and moisture contents can change due to changes in the soil matrix. The placement of a cap layer is one example of applied normal stress on a soil. These changes in void ratio and moisture content are categorized as immediate settlement, primary consolidation, and secondary consolidation [Das, 2005].

Immediate Settlement

Immediate settlement is caused by the elastic deformation of the soil matrix without any change in the moisture content. Calculation of immediate settlement depends primarily on the elastic modulus of the soil, E_s. Immediate settlement is primarily observed in sands, and is a negligible component of total settlement in clays and sediments [Das, 2005]. Settlement of the glacial sands lying beneath the native alluvial sediments is modeled using immediate settlement. Based on the results of the settlement analysis, the immediate settlement within the glacial sands is expected to be low compared to the settlement calculated in the native alluvial sediments.

Primary Consolidation

Primary consolidation is caused by the relocation of solid particles within the soil matrix and the resulting expulsion of liquids from the soil matrix. These expelled liquids move through the matrix of the affected soil and the surrounding soil at the rate allowed by the permeability of the soil matrices. Primary consolidation is therefore a time-dependent mechanism. Calculation of primary consolidation depends on the thickness of the affected soil layer, the properties of the layers above and below the affected soil layer, the initial vertical effective stress (σ_0'), the change in vertical effective stress ($\Delta\sigma'$), the maximum historical vertical effective stress experienced by the soil layer (called the preconsolidation pressure, σ_p'), the initial void ratio of the soil layer (e_0), and the

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **81** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

---

compression and recompression indices (C_c and C_r, respectively). Primary consolidation is primarily observed in clays and sediments, and is a negligible component of total settlement in sands [Das, 2005].

The total expected primary consolidation settlement (S_p) can be calculated as follows:

$$S_p = \frac{C_r H}{1 + e_0} \log \frac{\sigma_p'}{\sigma_0'} + \frac{C_c H_{dr}}{1 + e_0} \log \frac{\sigma_0' + \Delta\sigma'}{\sigma_p'}$$

Where H is the thickness of the consolidating soil layer [Das, 2005].

As mentioned above, consolidation is a time-dependent mechanism. Solving the underlying governing differential equation results in a plot of degree of consolidation with depth for various isochrones (lines representing the variation of degree of consolidation over depth at a given time). The plot of degree of consolidation with depth for a soil layer which has equal drainage boundaries above and below is shown in Figure 1. The degree of consolidation at a given depth, U_z is defined as:

$$U_z = \frac{u_0 - u_z}{u_0} = 1 - \frac{u_z}{u_0}$$

Where u_0 is the initial excess pore water pressure and u_z is the excess pore water pressure at a given time [Das, 2005]. The dimensionless time factor T_v is defined as:

$$T_v = \frac{c_v t}{H_{dr}^2} ; c_v = \frac{k}{\gamma_w m_v}$$

Where c_v is the coefficient of consolidation, t is the elapsed time, H_{dr} is the drainage length which is half the total thickness of the consolidating layer in this case where the consolidating layer is doubly drained, k is the hydraulic conductivity, γ_w is the density of water, and m_v is coefficient of volume compressibility. Although, mathematically, primary consolidation is never complete, a time to a given average degree of consolidation (e.g., 95 or 99 percent) can be calculated and used in geotechnical design [Das, 2005].

			HPH106A
			Treatment Layer Design Evaluation
			Revision 0
			May 2017

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

Page   **82**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Secondary Consolidation

Secondary consolidation, or creep, is caused by the plastic deformation of the solid particles in the soil. This plastic deformation can also result in expulsion of liquids from the soil matrix. Secondary consolidation is primarily observed in soft clays and sediments, and is a negligible component of total settlement in sands and stiff clays. Secondary consolidation can be more important than primary consolidation in organic and highly compressible inorganic soils [Das, 2005]. The expected secondary consolidation settlement (S_s) can be calculated as follows:

$$S_s = \frac{C_\alpha H}{1 + e_p} \log\left(\frac{t_2}{t_1}\right)$$

Where C_α is the secondary compression index, H is the thickness of the soil layer, e_p is the void ratio at the end of primary consolidation, and t_1 and t_2 are times [Das, 2005].

As can be seen from the equation above, secondary consolidation is a constant linear process. Geotechnical designs must therefore select a finite time (e.g., 30 or 100 years) for calculation of secondary consolidation.

Hydraulic Gradient

At the instant of the application of the load on top of the consolidating layer, the full force of the load is resisted by the fluid within the voids of the soil. This results in an instantaneous uniform excess pore pressure. The excess pore pressures will then begin dissipating immediately as the load is transferred to the soil particles, with the pore pressures closer to the drainage boundaries dissipating more quickly than the pore pressures at the center of the consolidating layer. This results in a hydraulic gradient which can be calculated as follows:

$$i = \frac{\delta u}{L}; @t = 0, i = \frac{u_0}{L}$$

Where i is the hydraulic gradient, δu is the difference in excess pore pressure between two points, and L is the distance between those two points. Immediately after the placement of the cap, the hydraulic gradient is equal to the load applied divided by the drainage length, or half the thickness of the consolidating layer. This hydraulic gradient will then begin to drop as the excess pore pressures dissipate, in accordance with the above equations describing primary consolidation (and as shown in Figure 1).

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

It is anticipated that the cap that is to be placed on top of the drained sediments will be approximately 5 ft thick, with an average total unit weight of 127 pounds per cubic foot (pcf). The placement of the cap will therefore apply an effective vertical stress of 323 pounds per square foot (psf). After accounting for the reduction in stress due to the dredging of the soft sediments, the net change in effective vertical stress in RTA1 outside of the ISS zones varies from 42.7 to 273.2 psf (Geosyntec, 2016b). The instantaneous average hydraulic gradient within the consolidating layer at the moment of cap placement assumes that the full effective vertical stress of the cap is translated to excess pore pressure at the center of the consolidating layer, while zero pore pressure develops at the boundaries of the consolidating layer. The instantaneous average hydraulic gradient within the consolidating layer at the moment of cap placement ranges from 0.5 to 33.1. However, the high end of the range of the hydraulic gradient can be misleading, as it is generated within very thin layers of native alluvial sediments (<0.25 ft thick), which could only contain a limited volume of potentially migrating DNAPL that could be expressed. Excluding layers of native alluvial sediment that are thinner than 1 ft results in a range of hydraulic gradient from 0.5 to 8.0.

The dissipation of this hydraulic gradient would be consistent with the dissipation of excess pore pressure during primary consolidation, which is explained above, as the excess pore pressure drains away from the top half of the layer through the top drainage boundary and from the bottom half of the layer through the bottom drainage boundary. The coefficient of consolidation, c_v, for the native alluvial sediments is estimated to vary from 0.2 to 0.0002 cm²/s across RTA1 (Geosyntec, 2016c). This would translate to a range of approximately 4.4 hours to 182 days for 90 percent (%) of the excess pore pressure to dissipate from within a 4-ft thick layer of native alluvial sediment. However, as the T_v parameter is nonlinear with time (as can be seen in Figure 1), it would take approximately 1 hour to 42.2 days for 50% of the excess pore pressure to dissipate from within the same layer.

Change in Porosity due to Consolidation

As consolidation progresses and excess pore pressures dissipate, the consolidating layer loses a volume corresponding to the volume of water expelled during consolidation. Since the volume of the solids has not changed, this means that the volume of voids has been reduced proportionally to the settlement. As the volume of the voids reduces, so do the void ratio and the porosity of the soil. As mentioned above, the porosity of a soil is defined as:

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

$$n = \frac{V_{voids}}{V_{total}}$$

Where V_{voids} is the volume of the voids and V_{total} is the total volume of the soil. For one-dimensional consolidation, V_{voids} and V_{total} can be assumed to have units of length, and V_{total} is equivalent to the thickness of the layer under consideration. The pre-consolidation and post-consolidation porosities can therefore be defined as follows:

$$n_0 = \frac{V_{voids,0}}{V_{total,0}}; n_1 = \frac{V_{voids,1}}{V_{total,1}}$$

The pre-consolidation and post-consolidation thicknesses of the layer can be defined as

$$H_0 = V_{total,0}; H_1 = V_{total,1} = H_0 - S = V_{total,0} - S$$

Since primary consolidation is entirely due to reduction in voids due to expulsion of water, the pre-consolidation and post-consolidation volume of voids can be defined as:

$$V_{voids,1} = V_{voids,0} - S$$

The change in porosity with settlement in a particular layer can therefore be calculated as:

$$n_1 = \frac{\left(n_0 - \frac{S}{H_0}\right)}{1 - \frac{S}{H_0}}$$

In RTA1, the porosity of the native alluvial sediments ranges from 0.30 to 0.87, with an average porosity of 0.50. For the range of settlements calculated for the native alluvial sediments in the settlement package (Geosyntec, 2016b), and using the equation above, the porosities within the top 1 ft of the consolidating alluvial sediments would decrease by 0.02 to 0.04 (2 to 13 percent reduction in pore space), while the porosities within a layer 5 ft below the dredge surface would decrease by 0.01 to 0.02 (1 to 2 percent reduction in pore space). These changes in porosity of the native alluvium would occur according to the rate shown in Figure 1, at the corresponding depth into the consolidating layer.

				HPH106A
				Treatment Layer Design Evaluation
				Revision 0
				May 2017

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

Page **85** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**		Project No:	**HPH106A**

POTENTIAL FOR CONSOLIDATION-INDUCED DNAPL EXPRESSION

Introduction

DNAPLs are organic liquids, typically with minimal solubility in water. In DNAPL-saturated sediments, DNAPL occupies a portion of the void space that would otherwise be occupied by water, as illustrated in Figure 2. The potential for DNAPL migration is a function of DNAPL saturation (and connectivity phase through the pore space), its physical properties and pore fluid pressures. DNAPL saturation and capillary pressure are influenced by porosity (pore size) and hydraulic gradient, which are predicted to change due to primary consolidation of the native alluvial sediments.

In Canal sediments, DNAPL is typically the non-wetting phase and pore water is the wetting phase. The capillary pressure (P_C) is defined as the difference between the non-wetting and wetting-phase pressures ($P_C = P_{nw} - P_w$). The capillary pressure is a non-linear function of saturation, where higher P_C values are associated with higher DNAPL saturation and lower pore water saturation. For DNAPL to be mobilized, the capillary pressure must exceed the displacement pressure (P_d). For DNAPL to migrate or be expressed (i.e. form a connected phase through the pore space), the capillary pressure must exceed the pore entry pressure (P_e) and displace the water (as illustrated in Figure 3).

Higher density DNAPL and DNAPL trapped in a soil matrix with smaller pore sizes (e.g., clays) require more pressure to be displaced than lower density DNAPL and DNAPL trapped in a soil matrix with larger pore sizes (e.g., sands). When a soil has low DNAPL saturation, DNAPL can be trapped in the soil matrix as residual DNAPL, which exhibits a capillary pressure of zero and typically cannot be mobilized by water pressure, as illustrated in Figures 2 and 3. The amount of the residual saturation DNAPL depends on physicochemical properties of the DNAPL, the capillary pressure of the DNAPL during emplacement (terminal pressure (P_t), in Figure 3), and the physical and chemical characteristics of the soil particles and matrix.

When a load is applied to a soil matrix (e.g., cap placement) excess pore pressure is generated in the soil matrix, resulting in a hydraulic gradient due to primary consolidation. As explained above, primary consolidation, and the resulting hydraulic gradient, is greatest at the instant of load application and decreases over time. The reduction in porosity due to consolidation is greatest immediately below the applied load and decreases with depth. Several studies, discussed below, have looked at the potential for this consolidation-induced NAPL expression and flow.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **86** of **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

NAPL Characteristics Affecting Mobilization due to Consolidation

Five studies were reviewed which applied a load to NAPL-containing sediments and evaluated the resulting expressed fluid. The methodologies of these studies varied, including:

1) applying a load to an artificial mixture of NAPL-containing kaolinite and bentonite using a hydraulically-loaded consolidation cell and collecting the expressed fluid [Thornley et al., 2006];
2) placing a sand cap on NAPL naturally occurring in sediments in a triaxial cell and incrementally increasing pressure, then examining the cap following the test to evaluate NAPL migration [Kim et al., 2009];
3) applying a load to NAPL naturally occurring in sediments using a triaxial cell and collecting the expressed fluid [Moretti, 2008];
4) applying a load to an artificial mixture of NAPL-containing kaolinite and NAPL naturally occurring in sediments using a triaxial cell and collecting the expressed fluid [Erten, 2012], and;
5) applying a load to NAPL-containing sediments sampled in Gowanus Canal using a triaxial cell.

The reported liquid limits (LLs) of the NAPL-containing sediments and clays used in these studies varied from 30 to 194 [Thornley et al., 2006; Kim et al., 2009], with one outlier sample of bentonite having an LL of 420 [Thornley et al., 2006]. The reported plasticity indices (PIs) of the NAPL-containing sediments and clays used in these studies varied from 12 [Thornley et al., 2006; Erten, 2012] to 122 [Kim et al., 2009] with one outlier sample of bentonite having a PI of 380 [Thornley et al., 2006]. A broad range of initial NAPL saturations (~10 to 70% of pore space) were also investigated [Kim et al., 2009; Erten, 2012]; however, a DNAPL-type similar to that encountered in RTA1 and 4th Street Turning Basin (TB4) was only tested in one of the studies [Kim et al., 2009]. The LLs, PIs, NAPL types, concentrations, and saturations of the samples tested in each of the studies is presented in Table 1.

The studies generally showed that, at low saturations of NAPL (i.e., below approximately 18% pore fluid saturation [PFS]), minimal to low NAPL expression is expected at loads or hydraulic gradients corresponding to the placement of cap material, due to the NAPL being present at residual saturation values (i.e. trapped by capillary forces in the pore structure of the sediments). The NAPL expression during consolidation measured by Thornley et al. [2006] can be attributed to the high hydraulic gradients generated by the applied loads. After the initial bedding-in, an

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **87** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**	Project No:	**HPH106A**

increase in load of between 8.3 and 9.8 kPa was applied. This corresponds to a placement of approximately 3 to 3.5 ft of cap material instantaneously. Kim et al. [2009] also mentioned a similar threshold of pore water velocity of 10 cm/day, beyond which some NAPL expression would be expected. For a 2-ft thick sediment layer with a hydraulic conductivity of approximately 1×10^{-4} cm/s, a pore water velocity of 10 cm/day would result from approximately 2 ft of instantaneously placed cap. For the analysis, an upper bound design cap thickness of 4.5 ft is assumed, consisting of 6 inches of sand, 2 ft of treatment layer, and 2 ft of isolation/habitat/armor layer, which is expected to result in a maximum settlement of approximately 3.5 inches.

The study by Thornley et al. [2006] also indicated that LLs and PIs of the NAPL-containing sediments could be an indicator of the rate of NAPL expression during consolidation. NAPL-containing bentonite, with an order of magnitude greater LL and PI than NAPL-containing kaolinite, expressed an order of magnitude more NAPL than the NAPL-containing kaolinite, when measured as weight of NAPL per weight of dry clay. Similarly, the Cuttings (B) (NAPL-containing drilling cuttings with a higher LL and PI) had more expressed NAPL than Cuttings (A) (NAPL-containing drilling cuttings with a lower LL and PI), when measured as weight of NAPL per weight of dry clay. However, the expressed fluid from Cuttings (B) had a lower concentration of NAPL, when measured as weight of NAPL per volume of expressed fluid, than the expressed fluid from Cuttings (A). This may be because a material with a higher LL can hold more water when saturated, and therefore has more water to release during consolidation. In general, soils with a high LL would likely tend to express more NAPL.

The properties of the sediment samples collected during the Pre-Design NAPL Investigation (PD-8) generally fall within the ranges of these studies (1) to (4), with LLs ranging from 13 to 83 (with a median LL of 17), PIs ranging from non-plastic to 52 (with the median sample being non-plastic), and with DNAPL saturations of approximately 10 to 80% within 0-10 ft of the dredge line in RTA1 and TB4, where all the sediments sampled are expected to be capped [Geosyntec, 2016a]. NAPL redistribution and expression due to consolidation of three samples collected close to the interface between soft and native sediments in Gowanus Canal were investigated by Reible et al. [2013]. The samples contained 3 to 15 % hexane extractable matter (approximately equivalent to NAPL saturation of 17 to 51 % of pore space assuming the samples contained DNAPL similar to that present in RTA1 or TB4[1]). All samples were subjected to loadings, equivalent to up to 10 feet of sand, in five stages. No samples released measurable quantities of NAPL as a result of this

---

[1] Reible et al [2013] state that hexane extraction likely over estimates the NAPL content (and therefore saturation) in the samples

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **88** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

---

loading. Trace observations of expressed NAPL however indicate that the sediments could lead to transient sheens if disturbed. Significantly, only trace volumes of NAPL (that could lead to sheens if disturbed) were expressed even though the samples were subjected to volume reduction during consolidation of up to 16 to 18%. Post-consolidation sampling showed that some redistribution of NAPL and water had occurred in the samples despite negligible NAPL release.

Based on the results of these studies, it might therefore be expected that only limited volumes of DNAPL (if any) would potentially be expressed as a result of consolidation due to cap placement. Most of the capped sediments, such as those noted above in RTA1 and TB4 [Geosyntec, 2016a], contain DNAPL at saturations that are at or below the threshold proposed by Erten [2012] and approximate saturations of samples tested by Reible et al. [2013]. However, the study by Erten [2012] investigated NAPLs with contrasting properties (less dense than water and more viscous) to the DNAPL encountered in RTA1 and TB4, that influence the potential for DNAPL to migrate. Furthermore, other factors controlling the potential for DNAPL in Canal sediments to be expressed into the cap include the volume of DNAPL available for migration (depending on excess saturation above a threshold for migration and thickness of the DNAPL-impacted layer) and the distance between the DNAPL and cap that were not studied directly by Reible et al. [2013].

DNAPL Expression Potential due to Consolidation of Native Alluvial Sediments

A preliminary evaluation of the potential for DNAPL to be expressed into the cap due to consolidation has been performed using sample data and migration modeling conducted as part of the work completed during the Pre-Design NAPL Investigation (PD-8) and predicted hydraulic gradients and porosity reductions described above.

The DNAPL characteristics pertinent to this review include:

- Initial estimates for DNAPL residual saturation (17% of pore space) and threshold saturation for DNAPL migration in the Site sample data are 17% and 20%, respectively;
- The majority of DNAPL encountered within 0-10 ft of the dredge line in RTA1 and TB4 is below residual saturation and is immobile. Hydraulic gradients induced by consolidation will also be insufficient to mobilize residual DNAPL;
- Higher DNAPL saturations are generally present ≥ 5 ft below the dredge line with only localized exceedances of the migration saturation threshold at shallower depths;

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | Project No: | **HPH106A** |

- The predicted reductions in porosity could engender relative increases in DNAPL pore fluid saturation and potential for migration, in particular for DNAPL layers within 1-2 ft of the cap;
- The predicted magnitude and duration of increases in hydraulic gradient due to consolidation could be sufficient to cause DNAPL exceeding the migration saturation threshold that is present within the upper half of the alluvium to migrate towards and potentially into the cap.

DNAPL migration models developed as part of the Pre-Design NAPL Investigation (PD-8) have been repurposed to make a preliminary assessment of the potential for DNAPL expression into the cap. Two migration models have been modified and applied:

- The *DNAPL volume accommodation model* predicts DNAPL saturation in sediments directly beneath the cap assuming uniform redistribution following DNAPL migration from layers exceeding the migration threshold. The model was modified to account for relative increases in DNAPL saturation due to porosity reductions by depth below the cap;
- The *1D two-phase flow model* (UTCHEM) predicts the vertical distance migrated by DNAPL for applied upward hydraulic gradients. Models simulating hydraulic gradients between 1 and 10 were applied, consistent with the order of magnitude gradients predicted due to consolidation of the alluvial sediments. The change in porosity was not simulated.

The DNAPL drainage characteristics (i.e., migration saturation threshold) were assumed to be the same as in the pre-capping condition and the hydraulic gradient due to consolidation were conservatively assumed as constant in time (steady-state).

The models were applied to assess potential migration of DNAPL within the native alluvial sediments above the midline of the stratum[2], which indicated potential DNAPL expression in RTA1 and TB4, covering an estimated area of up to 39,625 ft^2 (Table 2). The volume of DNAPL potentially expressed is estimated to be between <0.0001 and 0.022 ft^3 DNAPL/ft^2 (based on predicted excess DNAPL saturation >20% saturation within the alluvial sediments above the

---

[2] The direction of porewater drainage due to consolidation, and therefore potential DNAPL migration and expression into the capping layer, is assumed to be upwards in sediments located above the midline of the native alluvial sediments layer (refer to Figure 1). Porewater drainage due to consolidation is downwards and into the glacial deposits within sediments below the midline of the alluvial stratum.

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

midline of the stratum), equating to <5.5 yd^3 total DNAPL volume (Table 2). The predicted locations of potential DNAPL expression are illustrated in Figure 4.

SUMMARY AND CONCLUSION

Based on the results in the literature studies and preliminary modeling evaluation, the potential for DNAPL expression into the cap due to consolidation is considered low (<5.5 yd^3 over 4,400 yd^2 plan area, representing 2,570 yd^3 Canal sediments). The evaluation is conservative and constrained by limiting assumptions. For example, the DNAPL migration saturation threshold is expected to be higher than currently estimated in consolidated sediments due to constriction of pore openings, while upper bound steady-state hydraulic gradients have been simulated.

The cap should be placed in lifts so as not to generate excessive hydraulic gradients or pore water velocities. Additionally, the volume of DNAPL predicted to be expressed (≤1.4 yd^3) due to the transient high-velocity conditions caused by the placement of cap could be addressed by the placement of the cap treatment layer.

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **91** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**			Project No:	**HPH106A**

REFERENCES

Das, B.M. (2005). "Fundamentals of Geotechnical Engineering, Second Edition." Thomson, Toronto, Ontario.

Erten, M.B., R. Gilbert, C.S. El Mohtar, D.D. Reible (2011) Development of a laboratory procedure to evaluate the consolidation potential of soft contaminated sediments, Geotechnical Testing Journal, 34, 5, September 2011

Erten, M. (2012). "Geotechnical Containment of Non Aqueous Phase Liquid Contaminated Sediments." PhD Thesis, The University of Texas at Austin.

Geosyntec Consultants (2016a). "PD-8 NAPL Investigation Report, Gowanus Canal Superfund Site, Brooklyn, NY – DRAFT." October 2016.

ITRC (Interstate Technology & Regulatory Council). 2015. Integrated DNAPL Site Characterization and Tools Selection (ISC-1). Washington, D.C.: Interstate Technology & Regulatory Council, DNAPL Site Characterization Team. www.itrcweb.org/DNAPL-ISC_tools-selection.

Kim, Y.S., Jafvert, C.T., Yoon, S., Hyun, S., Johnson, B. (2009). "Potential consolidation-induced NAPL migration from coal tar impacted river sediment under a remedial sand cap." *Journal of Hazardous Materials*, Vol. 162, Issues 2-3, 1364-1370.

Kueper, B. H. and Gerhard, J. I. (2014). "Hydraulic Displacement of Dense Nonaqueous Phase Liquids. In Chlorinated Solvent Source Zone Remediation. SERDP and ESTCP Remediation Technology Monograph Series

Kulasingam, R., Zhu, F., Beech, J.F., de Haven, P., and Brussel, L.K. (2011). "Estimating the Upward Flow Rate of Consolidation Water for Performance Modeling of Sediment Caps." Sixth International Conference on Remediation of Contaminated Sediments, New Orleans, LA

Moretti, L.K. (2008). "Evaluation of Capping NAPL-contaminated Sediment." Master's Thesis, The University of Texas at Austin.

Reible, D. D., Mohtar, C. L., Kim, M. and Martinez, A. 2013. Geotechnical Investigation of Gowanus Canal Sediments: NAPL Expression. For GEI Consultants Inc. April 1, 2013

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **92**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

Thornley, D.M., Wilkinson, W.B., and Parker, A. (2006). "A preliminary investigation of the release of oil from contaminated clays and other fine-grained sediments during consolidation." *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 39, Issue 4, 375-390.

Geosyntec▷ consultants	Beech and Bonaparte▷ engineering p.c. *an affiliate of Geosyntec Consultants*	

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**
Client:	**RD Group**	Project:	**Gowanus Canal Superfund Site**					Project No:	**HPH106A**		

TABLES

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

| | | Page | **94** | of | **101** |

CP: __DM__   Date: __5/18/2017__   APC: __JAW__   Date: __5/19/2017__   CC: __JAW__   Date: __5/19/2017__

Client: __RD Group__   Project: __Gowanus Canal Superfund Site__   Project No: __HPH106A__

Table 1. Summary of Previous Studies

Study	NAPL-Containing Sample	Liquid Limit (LL)	Plasticity Index (PI)	NAPL Type	Initial Weight of NAPL per Weight of Solids (mg/kg)	Initial NAPL Saturation (%)	NAPL expressed?
Thornley et al., 2006	Kaolinite + oil (A)	56.2	22.2	Lubricating oil	8,073	NR[1]	Average expressed concentration of 12-13 mg oil / kg dry clay or 35 mg oil / L expressed fluid
	Kaolinite + oil (B)	57.0	24.6		21,976	NR[1]	
	Bentonite + oil	420	380		59,572	NR[1]	Average expressed concentration of 128 mg oil / kg dry clay or 58 mg oil / L expressed fluid
	Cuttings (A)	29.8	11.8	Esters and poly-alpha-olefins	9,232	NR[1]	Average expressed concentration of 10 mg oil / kg dry clay or 79 mg/L expressed fluid
	Cuttings (B)	48.1	24.2		35,024	NR[1]	Average expressed concentration of 20 mg oil / kg dry clay or 48 mg/L expressed fluid
Kim et al., 2009	All samples	123-194	51-122	MAHs and PAHs (Coal Tar)	14,900-58,700	~10-30[2]	Minimal to none
Moretti, 2008	Lake Charles sample	NR[1]	NR[1]	NR[1]	520,000	NR[1]	Minimal to none
Erten, 2012	Kaolinite	96	12	Mineral oil	190,000-480,000	28-70	100% NAPL expression until NAPL concentration is ~120,000 mg/kg (~18% PFS[3]), then 100% water expression

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

Page **95** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

| Reible et al., 2013 | Native Alluvium, Gowanus Canal | NR[1] | NR[1] | Gowanus Canal NAPL | 28,100-151,100 | 17-52[2] | Trace NAPL in highest saturation sample |

Note:
1. NR = Not reported.
2. Estimated from reported sediment porosity and bulk density data assuming DNAPL density of 1.01 g/cm^3
3. PFS = pore fluid saturation

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page **96** of **101**

CP: **DM** Date: **5/18/2017** APC: **JAW** Date: **5/19/2017** CC: **JAW** Date: **5/19/2017**

Client: **RD Group** Project: **Gowanus Canal Superfund Site** Project No: **HPH106A**

Table 2. Summary of DNAPL Expression Estimates

Canal Area	Location Group	Predicted PFS after Capping (% Pore Space)			Predicted DNAPL Unit Volume Potentially Expressed into Cap (ft³ DNAPL/ft²)	Location Group Plan Area (ft²)	Predicted DNAPL Volume Potentially Expressed into Cap (yd³)
		0-1 ft BDL	1-2 ft BDL	2-10 ft BDL			
RTA1	MC0350-A	20.7	<20.0	<20.0	0.0004	3,468	0.05
	MC0800-A	31.6	45.5	<20.0	0.0066	3,503	0.86
	MC0850-B	24.3	<20.0	<20.0	0.0031	2,844	0.33
	MC1050-B	21.2	<20.0	<20.0	0.0025	3,765	0.35
	MC1700-A	21.6	<20.0	<20.0	0.0012	3,138	0.14
	MC2000-B	25.8	24.3	<20.0	0.0218	3,377	2.73
	MC2200-A	20.3	<20.0	<20.0	0.0001	3,187	0.01
	MC2250-A	20.4	21.3	<20.0	0.0018	2,960	0.2
TB4	4TB0000-A	60	<20.0	23.8	0.0018	8,178	0.55
	4TB0150-B	20.4	21.7	23.6	0.0021	2,211	0.17
	4TB0250-B	20.2	24.7	<20.0	0.0007	2,060	0.05
	4TB0550-B	21.5	<20.0	<20.0	0.0002	933	0.01
				Totals	**0.0423**	**39,624**	**5.45**

Note:
1. PFS – Pore fluid saturation
2. BDL – below dredge line
3. Threshold PFS above which DNAPL potentially migrating = 20 % pore space

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**

FIGURES

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.

an affiliate of Geosyntec Consultants

HPH106A
Treatment Layer Design Evaluation
Revision 0
May 2017

Page   **98**   of   **101**

CP: **DM**   Date: **5/18/2017**   APC: **JAW**   Date: **5/19/2017**   CC: **JAW**   Date: **5/19/2017**

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
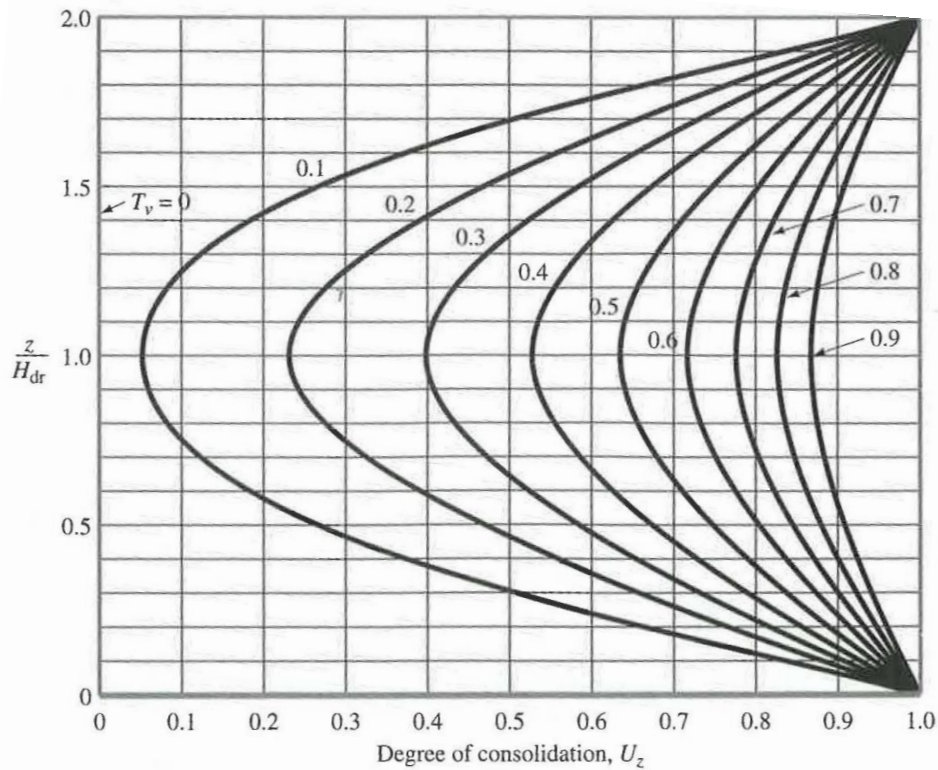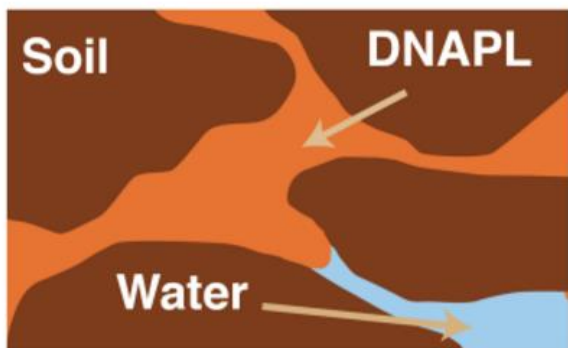

Figure 7.18 Variation of U_z with T_v and z/H_{dr}

**Figure 1. Variation of Excess Pore Pressure with Time in a Doubly-Drained Material
[Das, 2005]**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

| Client: | **RD Group** | Project: | **Gowanus Canal Superfund Site** | | Project No: | **HPH106A** |

Mobile DNAPL
DNAPL body is continuous and its capillary pressure is high enough to exceed groundwater pore entry pressure, displace groundwater, and migrate through the subsurface.

Potentially Mobile DNAPL
DNAPL body is continuous, but its capillary pressure is not high enough to exceed groundwater pore entry pressure; under current conditions, it will not displace groundwater and migrate. If conditions change (for example, drilling through a potentially mobile DNAPL body, soil fracturing), potentially mobile DNAPL may mobilize and begin migrating.
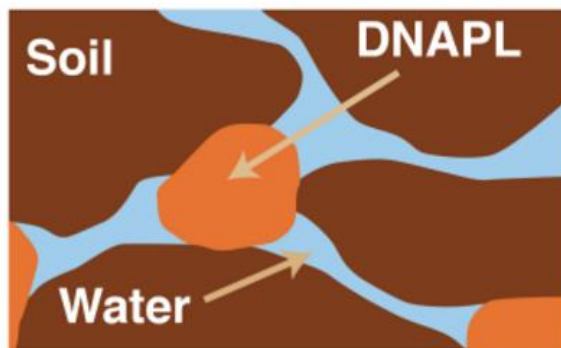
Immobile Residual Phase DNAPL
"Droplets" of DNAPL called ganglia are present in the pore spaces but are not connected to other DNAPL ganglia. They are immobile because they cannot exceed the capillary pressure and displace groundwater in the formation.

Figure 2. Mobility Characteristics of DNAPL: mobile, potentially mobile and immobile [ITRC, 2016]

		HPH106A
		Treatment Layer Design Evaluation
		Revision 0
		May 2017

Geosyntec▷
consultants

Beech and Bonaparte▷
engineering p.c.
an affiliate of Geosyntec Consultants

Page **100** of **101**

CP:	**DM**	Date:	**5/18/2017**	APC:	**JAW**	Date:	**5/19/2017**	CC:	**JAW**	Date:	**5/19/2017**
Client:	**RD Group**		Project:	**Gowanus Canal Superfund Site**					Project No:	**HPH106A**	

**Figure 3. Typical capillary pressure-saturation curve
[Kueper and Gerhard, 2014]**

| CP: | **DM** | Date: | **5/18/2017** | APC: | **JAW** | Date: | **5/19/2017** | CC: | **JAW** | Date: | **5/19/2017** |

Client: **RD Group**   Project: **Gowanus Canal Superfund Site**   Project No: **HPH106A**
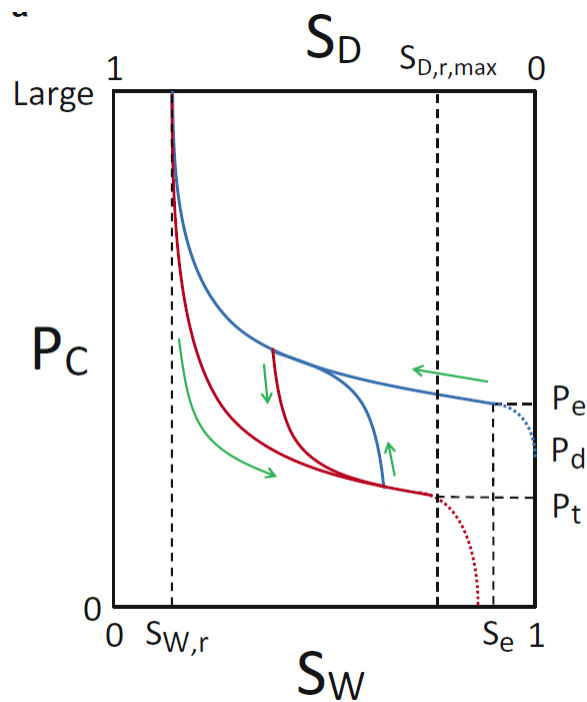

Figure 4. Zones of Potential DNAPL Expression Induced by Consolidation due to Capping in RTA1 and TB4 (Yellow polygons depict regions of potential DNAPL expression; green polygons depict regions where DNAPL expression is not anticipated)